Real-Time and Ultra-High Definition Video Transmission in Underwater Wireless Optical Networks

Dissertation by
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ABSTRACT

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Abdullah Fayez Saad Alhalafi

Oceans form about three quarters of our planet Earth, and house immense resources that are critical for future generations. Exploring and monitoring such resources is becoming essential to protect the effected ones by the irresponsible human behavior, and to discover new ones. The limitations of depths mandate the search for alternatives and where human divers become endangered. Using remotely operated vehicles is commonly used for marine explorations, while tethered to ships. To be fully autonomous and to avoid damaging the fragile marine environment, they must be equipped with wireless communication solutions that enable real-time control and feedback on their maneuvering and mobility. Also, the ultimate tool to monitor, inspect and repair underwater structures is to use video streaming to mimic the reality of those unseen parts of the world.

Existing underwater communications do not provide the necessary features to transmit video from the deep. Acoustic waves as well as the radio frequency waves are either limited in bandwidths or strongly attenuated by the water medium. On the other hand, wireless optical communication is an emerging technology that provides high transmission speeds and can enable video streaming underwater.

This motivates bringing wireless optical technologies for real-time video streaming underwater to a practical implementation by undertaking theoretical and experimental studies of systems and techniques that can provide optimized solutions within our
proposed framework. We present our video transmission architecture that facilitates
programmable system configurations. Software defined platforms provide us with the
means of configuring several setups to test our approach. In order to fully utilize
the available optical spectrum, we have additionally implemented several modulation
techniques in various laboratory scenarios. Real-time and ultra-high definition video
has been successfully demonstrated. The overall system performance and throughput
analysis have been provided. A thorough investigation of the system performance
under various underwater channel conditions was undertaken. Also, as the delay re-
sulting from queuing, when video packets are waiting for service, is key in time critical
applications, we derive the mathematical model and investigate the delay effects and
the packet dropping probability on the overall system performance when our setup is
extended to a multi-channel configuration.
“Have not the people, who have disbelieved (the Message), ever considered this: the heavens and the earth were at first one mass; then We parted them, and created every living thing from water? Do they not acknowledge (that this is Our Creation)?”

Explication of Surat Al-Anbiyaa (21:30).

“Our planet is a big, complex, intricate system and the ocean is the most poorly understood part of it. That system is under stress and we need to improve our understanding of how it works so that we can help preserve our home.”

Testimony of James Cameron;
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examination Committee Page</td>
<td>2</td>
</tr>
<tr>
<td>Copyright</td>
<td>3</td>
</tr>
<tr>
<td>Abstract</td>
<td>4</td>
</tr>
<tr>
<td>List of Abbreviations</td>
<td>10</td>
</tr>
<tr>
<td>List of Figures</td>
<td>13</td>
</tr>
<tr>
<td>List of Tables</td>
<td>16</td>
</tr>
<tr>
<td><strong>1 Introduction</strong></td>
<td>17</td>
</tr>
<tr>
<td>1.1 Problem statement and motivation</td>
<td>18</td>
</tr>
<tr>
<td>1.1.1 Point-to-point links for underwater real-time video</td>
<td>19</td>
</tr>
<tr>
<td>1.1.2 Bi-directional links for underwater UHD video with feedback</td>
<td>20</td>
</tr>
<tr>
<td>1.1.3 Multi-channel links end-to-end delay and blocking probability analysis for underwater video streaming</td>
<td>21</td>
</tr>
<tr>
<td>1.2 Contributions</td>
<td>22</td>
</tr>
<tr>
<td>1.2.1 Survey of the underwater wireless optical networks and communication systems</td>
<td>22</td>
</tr>
<tr>
<td>1.2.2 Underwater video streaming using point-to-point links</td>
<td>22</td>
</tr>
<tr>
<td>1.2.3 Underwater video streaming using bi-directional links</td>
<td>23</td>
</tr>
<tr>
<td>1.2.4 Underwater video transmission end-to-end delay analysis using multi-channels</td>
<td>25</td>
</tr>
<tr>
<td>1.3 Thesis Outline</td>
<td>26</td>
</tr>
<tr>
<td><strong>2 Background and developments</strong></td>
<td>27</td>
</tr>
<tr>
<td>2.1 Underwater resources</td>
<td>27</td>
</tr>
<tr>
<td>2.2 From ancient civilizations to modern age</td>
<td>29</td>
</tr>
<tr>
<td>2.2.1 History on light and optics research</td>
<td>29</td>
</tr>
<tr>
<td>2.2.2 Underwater exploration and photography</td>
<td>31</td>
</tr>
</tbody>
</table>
2.2.3 Underwater acoustic communications .............................................. 31
2.2.4 Underwater optical communications .............................................. 33

2.3 Challenges to underwater communications .............................................. 35
  2.3.1 Light wave interactions with water .............................................. 35
  2.3.2 Scattering and absorption ......................................................... 39
  2.3.3 Turbulence ............................................................................. 40
  2.3.4 Air bubbles ............................................................................ 40
  2.3.5 Existing communication limitations .............................................. 41

2.4 Recent developments on underwater wireless optical networks .............. 41
  2.4.1 Underwater wireless optical communications .................................. 42
  2.4.2 Limitations on video transmission underwater .................................. 43
  2.4.3 Multi-channel links for underwater wireless optical communications .... 44

2.5 Underwater vehicles ........................................................................ 46
2.6 Discussion ....................................................................................... 46

3 Real-time video transmission in underwater wireless optical networks .... 48
  3.1 System model ............................................................................. 48
  3.2 Experimental setup ...................................................................... 49
  3.3 Bit error rate calculation ............................................................... 54
      3.3.1 Synch bits detection and matching BER trigger ......................... 55
      3.3.2 BER moving average calculations ......................................... 58
  3.4 Experimental results and discussions .............................................. 58
      3.4.1 Visual analysis ....................................................................... 61
      3.4.2 Bit error rate analysis ............................................................ 63
      3.4.3 Video quality SSIM analysis .................................................... 64
  3.5 Discussions ................................................................................. 66

4 UHD video transmission over bi-directional underwater wireless optical networks .............................................. 68
  4.1 System model ............................................................................. 69
      4.1.1 Downlink transmitter module .................................................. 69
      4.1.2 Downlink receiver module ....................................................... 70
      4.1.3 Uplink transmitter module ....................................................... 70
      4.1.4 Uplink receiver module ........................................................... 71
  4.2 Experimental setup ...................................................................... 72
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.1</td>
<td>Downlink optics setup</td>
<td>72</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Uplink optics setup</td>
<td>74</td>
</tr>
<tr>
<td>4.3</td>
<td>OFDM Implementation</td>
<td>75</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Modulation techniques</td>
<td>75</td>
</tr>
<tr>
<td>4.3.2</td>
<td>OFDM details</td>
<td>77</td>
</tr>
<tr>
<td>4.4</td>
<td>Experimental results and discussions</td>
<td>78</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Visual analysis</td>
<td>78</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Throughput analysis</td>
<td>80</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Video quality PSNR analysis</td>
<td>86</td>
</tr>
<tr>
<td>4.5</td>
<td>Discussions</td>
<td>87</td>
</tr>
<tr>
<td>5</td>
<td>Video delay analysis and blocking probability in multi-channel underwater wireless optical networks</td>
<td>90</td>
</tr>
<tr>
<td>5.1</td>
<td>Proposed System Model</td>
<td>91</td>
</tr>
<tr>
<td>5.2</td>
<td>Analysis</td>
<td>95</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Video Transmission Time Delay</td>
<td>99</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Minimum Channel-Count</td>
<td>99</td>
</tr>
<tr>
<td>5.3</td>
<td>Numerical Results</td>
<td>100</td>
</tr>
<tr>
<td>5.4</td>
<td>Discussions</td>
<td>108</td>
</tr>
<tr>
<td>6</td>
<td>Concluding Remarks</td>
<td>109</td>
</tr>
<tr>
<td>6.1</td>
<td>Summary</td>
<td>109</td>
</tr>
<tr>
<td>6.2</td>
<td>Future Work</td>
<td>111</td>
</tr>
</tbody>
</table>

References | 112
LIST OF ABBREVIATIONS

ACK  Acknowledgment
APD  Avalanche Photodiode
AUV  Autonomous Underwater Vehicle
BER  Bit Error Rate
Bi-DIR  Bi-Directional
BLER  Block Error Rate
CRC  Cyclic Redundancy Check
CRS  Cell-specific Reference Signals
dB  Decibles
DL  Down-Link
DOM  Dissolved Organic Matters
DSP  Digital Signal Processing
E2E  End-to-End
FPGA  Field Programmable Gate Array
FSO  Free-Space Optical
FWHM  Full-Width at Half-Maximum
Gbps  Gigabit per second
GHz  Gigahertz
Hz  Hertz
ISI  Inter-Symbol Interference
Kbps  Kilobit per second
kHz  Kilohertz
Km  Kilometers
LD  Laser Diode
LED  Light-Emitting Diode
LOS  Line-of-Sight
m  Meters
MAC  Medium Access Control
Mbps  Megabit per second
MCS  Modulation and Coding Scheme
NACK  No Acknowledgment
NEP   Noise Equivalent Power
NLOS  None Line-of-Sight
nm    Nanometers
NOAA  United States National Oceanic and Atmospheric Administration
OCDMA Optical Code Division Multiple Access
OFDM  Orthogonal Frequency Division Multiple Access
OOC   Optical Orthogonal Code
OOK   On-Off Keying
P2P   Point-to-Point
PDCCH Physical Downlink Control Channel
PDSCH Physical Downlink Data Shared Channel
PIM   Particulate Inorganic Matters
POM   Particulate Organic Matter
PSK   Phase-Shift Keying
PSNR  Peak Signal-to-Noise Ratio
PSS   Primary Synchronization Sequence
PUSCH Uplink Data Shared Channel
PVC   Polyvinyl Chloride
QAM   Quadrature Amplitude Modulation
QoS   Quality of Service
QPSK  Quadrature Phase Shift Keying
RF    Radio Frequency
ROV   Remotely Operated Vehicle
SINR  Signal-to-Interference-Noise-Ratio
SNR   Signal-to-Noise Ratio
SSIM  Structural Similarity
TB    Transport Block
UDP   User Datagram Protocol
UHD   Ultra-High Definition
UL    Up-Link
USRPR Universal Software Radio Peripherals
USRPR-RIO Universal Software Radio Peripheral-Reconfigurable Input/Output
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>UWOC</td>
<td>Underwater Wireless Optical Communication</td>
</tr>
<tr>
<td>UWON</td>
<td>Underwater Wireless Optical Networks</td>
</tr>
<tr>
<td>UWSN</td>
<td>Underwater Wireless Sensor Networks</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>Video packet length</td>
<td>49</td>
</tr>
<tr>
<td>3.2</td>
<td>Digital communications model for the transmitter and the receiver</td>
<td>49</td>
</tr>
<tr>
<td>3.3</td>
<td>Actual photograph of the water tank showing: (a) laser driver mount, (b) collimator lens, (c) attenuator, (d) green laser beams, (e) mirrors, (f) mirrors, (g) focusing lens, (h) avalanche photodiode (APD)</td>
<td>50</td>
</tr>
<tr>
<td>3.4</td>
<td>Characteristics of the 520 nm LD at 25°C: L-I-V curves</td>
<td>51</td>
</tr>
<tr>
<td>3.5</td>
<td>Characteristics of the 520 nm LD at 25°C: optical spectra with increasing bias currents</td>
<td>52</td>
</tr>
<tr>
<td>3.6</td>
<td>Schematics of the underwater video streaming system over a reconfigurable wireless optical link, SMA: SubMiniature version A connectors, SDR: Software Defined Radio</td>
<td>53</td>
</tr>
<tr>
<td>3.7</td>
<td>MT Calculate BER after Trigger (PN Sequence) Virtual Instrument</td>
<td>55</td>
</tr>
<tr>
<td>3.8</td>
<td>BER threshold graph</td>
<td>56</td>
</tr>
<tr>
<td>3.9</td>
<td>BER confidence graph</td>
<td>57</td>
</tr>
<tr>
<td>3.10</td>
<td>Block diagram for BER detection in LabVIEW</td>
<td>58</td>
</tr>
<tr>
<td>3.11</td>
<td>Synch bits detection and BER trigger threshold</td>
<td>59</td>
</tr>
<tr>
<td>3.12</td>
<td>Average BER calculation</td>
<td>60</td>
</tr>
<tr>
<td>3.13</td>
<td>Block Diagram of BER calculation in LabVIEW</td>
<td>60</td>
</tr>
<tr>
<td>3.14</td>
<td>Clear water: (8-PSK) (a) eye diagram, (b) constellation graph, (c) transmitted video, (d) received video</td>
<td>61</td>
</tr>
<tr>
<td>3.15</td>
<td>Clear water: (8-QAM) (a) eye diagram, (b) constellation graph, (c) transmitted video, (d) received video</td>
<td>61</td>
</tr>
<tr>
<td>3.16</td>
<td>Coastal water: (a) transmitted video; received videos for: (b) 8-PSK, (c) 8-QAM</td>
<td>62</td>
</tr>
<tr>
<td>3.17</td>
<td>Harbor I water: (a) transmitted video; received videos for: (b) 8-PSK, (c) 8-QAM</td>
<td>62</td>
</tr>
<tr>
<td>3.18</td>
<td>Harbor II water: (a) transmitted video; received videos for: (b) 8-PSK, (c) 8-QAM</td>
<td>63</td>
</tr>
<tr>
<td>3.19</td>
<td>BER of received videos</td>
<td>64</td>
</tr>
<tr>
<td>3.20</td>
<td>SSIM results for video images</td>
<td>66</td>
</tr>
</tbody>
</table>
4.1 Block diagram of the system.

4.2 Actual photograph of the water tank showing: Downlink Channel (a) Green laser and driver mount, (b) collimator lens, (c) mirror, (d) green laser beams underwater, (e) mirror, (f) focusing lens, (g) avalanche photodiode (APD), and Uplink Channel (h) Blue laser and collimator lens, (i) mirror, (j) blue laser beams underwater, (k) mirror, (l) focusing lens, (m) avalanche photodiode (APD).

4.3 Characteristics of the 520 nm LD at 25°C: (a) L-I-V curves (b) optical spectra with increasing bias currents.

4.4 Characteristics of the 450 nm LD at 25°C: (a) L-I-V curves (b) optical spectra with increasing bias currents.

4.5 Schematics of the bi-directional underwater video communication system over a reconfigurable wireless optical link.

4.6 Constellation graph harbor II water: (a) 64-QAM, (b) 16-QAM, (c) QPSK, (d) feedback QPSK.

4.7 Video snapshot, harbor II water, 64-QAM, 4K resolution: (a) transmitted video, (b) received video underwater.

4.8 Another video snapshot, harbor II water, 64-QAM, 4K resolution: (a) transmitted video, (b) received video underwater.

4.9 Average throughput versus video resolution.

4.10 Throughput over time for the 1080 and 480 video resolutions.

4.11 Throughput over time for the 4K UHD video resolution in harbor II water using: (a) 16-QAM, (b) 64-QAM, (c) QPSK, and in (d) clear water using QPSK.

4.12 Throughput over time for the 4K video resolutions in harbor II water for QPSK, 16-QAM, and 64-QAM: (a) 15 minutes (b) zooming into 3 minutes only.

4.13 Throughput over time for the 4K video resolutions using 64-QAM in clear water and harbor II water: (a) 15 minutes (b) zooming into 3 minutes only.

4.14 Average PSNR for video resolutions 480, 720, and 1080 versus modulations in all water types.

4.15 Average PSNR for 4K UHD video resolutions versus modulations in all water types.

5.1 An overview of the multi-channel underwater wireless optical system.
<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.2</td>
<td>Multi-channel System model and queue overview</td>
<td>92</td>
</tr>
<tr>
<td>5.3</td>
<td>Blocking probability vs. preset QoS constraint for 4 channels</td>
<td>102</td>
</tr>
<tr>
<td>5.4</td>
<td>Response time (simulation and analytical) vs. preset QoS constraint</td>
<td></td>
</tr>
<tr>
<td></td>
<td>for (a) 1 channel, (b) 2, (c) 3, and (d) 4 channels</td>
<td>103</td>
</tr>
<tr>
<td>5.5</td>
<td>Response time for QoS=90% versus number of channels (simulation)</td>
<td>104</td>
</tr>
<tr>
<td>5.6</td>
<td>Response time for QoS=70% versus number of channels (simulation)</td>
<td>105</td>
</tr>
<tr>
<td>5.7</td>
<td>Response time for QoS=80% versus number of channels (simulation)</td>
<td>106</td>
</tr>
<tr>
<td>5.8</td>
<td>PDF of the proposed model with general distributions</td>
<td>107</td>
</tr>
</tbody>
</table>
LIST OF TABLES

3.1 Representative absorption, scattering and total attenuation coefficients 54
4.1 Representative absorption, scattering and total attenuation coefficients 75
5.1 Notations ................................................................................. 95
6.1 Summary of technological developments ................................. 111
Chapter 1

Introduction

The search for signs of life in the outer space have lead human expeditions to outreach to thousands of kilometers far away planets in our solar system and beyond. On the contrary, the oceans deep located only few kilometers away, on the same planet where we live, but it is ironic that we know very little about it. The oceans having great influence on weather, controlling temperature, and holding necessities for many sources of lives, transport, economies, and an inspiration to many [1]. It is becoming more vital while the world’s population is projected to be 9.7 billions in 2050 [2], to facilitate monitoring the existing natural resources and continuing the discovery for new ones within the boundaries of our planet that are necessary to maintain prosperity and well-being for our future generations [3].

Light when reflected on objects enable us to see their beauty, discover their details and understand their behaviour to better utilize them for human being benefits. When those objects are hidden by the oceans depths, we wish to use other light properties to virtually see those remote locations, and transfer what we see using light to a more suitable locations accessible by humans. Oceans, hold the promise as our final frontier where the untouched depths still remain full of mysteries and natural resources that humans have not been able to reach and uncover so far. Those oceans cover more than two thirds of our planet and host those vast resources critical to our living.

This thesis aims to discuss the real-time and Ultra-High Definition (UHD) video transmission using Bi-Directional (Bi-DIR) Underwater Wireless Optical Networks (UWON) with feedback links. The analysis is based on practical implementations
performed through extensive experimental studies on several setups under the pro-
posed system configurations and employing different channel conditions. The perfor-
mance aspects of the video transmission are thoroughly investigated experimentally
and theoretically to assess the received video quality, the overall optimized system
performance when deployed into the underwater channel and under various wireless
environment considerations. The analysis is extended to mathematically investigate
the model for the associated End-to-End (E2E) delay components that are resulting
from the generated queues when video packets are waiting for service in a multi-
channel configuration.

1.1 Problem statement and motivation

The exploration of ocean’s underwater resources continues to be of interest to mankind
for thousands of years. Initially human used helping exploration tools such as ships,
which eventually evolved through the years to using submarines, Remote Operated
Vehicles (ROVs), Autonomous Underwater Vehicles (AUVs) and underwater robots.
The limitations of depths and constraints of pressure remain challenging for scientific
explorers and that resulted in discovering only 5% of the oceans as per United States
National Oceanic and Atmospheric Administration (NOAA) [4].

In order to facilitate human telepresence without causing any harm to divers, or
disruptions to the marine environment, we aim to explore wireless communication
technologies for underwater video transmission as a tool to aid and revolutionize un-
derwater explorations. Due to the limitations in exiting underwater communications
(Acoustic and RF), we utilize the state-of-the-art Underwater Wireless Optical Com-
munication (UWOC) technologies. The real-time transmission of big data in general
is a desirable tool that many industries are looking for in the recent years. A ma-
jor requirement comes from the oil reservoirs optimization and management to make
critical decisions that can enhance the safety and integrity of the field infrastructu-
res. Also huge networks of subsea pipelines, cables and steel structures need to be inspected and repaired regularly. The cost of vehicles that are tethered to ships is huge for offshore operations. The conventional methods of sending divers are posing safety and life threatening concerns in deep and dangerous locations.

Earlier, few studies have focused on underwater video transmission and utilized the available bandwidth at that time. In 2005, Chancey performed an UWOC based video experiment on 4.6 Meters (m) clear water channel with 10 Megabit per second (Mbps) speed [5]. In 2007, Baiden et al. [6] also achieved a 10 Mbps system to transmit video information underwater over 10 m on Long Lake in Sudbury, Ontario. The AquaOptical II video transmission prototype, as in [7], used an array of 18-Ligh-Emitting Diodes (LEDs) transmitter and had a limit of 4 Mbps bandwidth. Also, an externally modulated data in a water tank with different visibility levels was demonstrated in [8] as an UWOC video experiment. These experiments have established and shown the potential of using UWOC for video streaming underwater. However, the received video quality and coverage ranges remain challenging.

We provide a thorough analysis of our proposed framework, which aims to enhance the quality of the received video, transmission speed, and the overall system performance for streaming video underwater. The proposed and implemented solutions that are provided by this thesis can fold into the following three areas.

1.1.1 Point-to-point links for underwater real-time video

In the first part of this thesis [9], we propose a low-power, cost-effective, and UWON based real-time video system employing Quadrature Amplitude Modulation (QAM) and Phase-Shift Keying (PSK) modulations. We evaluate the performance of the systems under various underwater channel link conditions and analyze both overall Bit Error Rate (BER) and video quality.

The experimental setup for real-time video streaming is using green laser sources.
We implemented Quadrature Phase Shift Keying (QPSK) and up to 8-QAM modulations in different underwater channels. The performance results demonstrated not only that video streaming is possible in one of the most turbid ocean water types, but also with good quality. We also survey the other researchers work who achieved video streaming below 10 Mbps. Those fascinating implementations as well as our work considered performing only uni-directional communications concept where data streams are sent from a transmitter to a receiver without any feedback on the receiver status, acknowledgements, or channel conditions.

1.1.2 Bi-directional links for underwater UHD video with feedback

In the second part of our work [10], we propose using Bi-DIR communication links for the purposes of underwater UHD and live video streaming on the downlink channels while providing the feedback control messages on the uplink channels. The additional uplink channel provides necessary feedback about the channel conditions, the possibility of using this to transmit and receive control messages, and real-time commands for maneuvering the ROVs. Furthermore, when a wireless optical feedback link is established, movements of multiple robots can be coordinated where the ROVs can move freely and send signaling data and receive further maneuvering instructions in real-time. The feedback received as well on the underwater channel conditions enables the instantaneous throughput adaptations to the noise levels and transmission power, and thus helps in reducing the energy loss while improving the modulation and coding schemes.

In a nutshell, we experimentally demonstrate the feasibility of the proposed systems and evaluate the performance under higher orders of QAM implemented with Orthogonal Frequency Division Multiple Access (OFDM) modulations. We examine our system by deployments in various underwater channel conditions and analyze the
throughput and quality of the received UHD live video streams. The results reveal that UHD video streaming is possible not only in the traditional uni-directional communication setup but also where feedback control messages are established through Bi-DIR links.

1.1.3 Multi-channel links end-to-end delay and blocking probability analysis for underwater video streaming

In the third part of our work [11], we provide analytical study that will enable researchers to make the best design of network topologies to meet the optimum Quality of Service (QoS) for the delay and packet loss when using UWON in a multi-channel configuration. Also, to provide researchers with the fundamental performance means to design an optimal routing policy for contingency planning and to overcome the None Line-of-Sight (NLOS) situations. Moreover, we hope to help engineers design a multi-channel system with optimal capacity assignment to each underwater wireless optical channel. In order to make this possible, we examine the performance of video transmission over an UWON system that is employing multi-channel diversity gain from a single sender through multiple channels underwater to a single receiver. We examine this network using an $M/G/1$ queuing theory model to quantify the system’s performance. We develop an approximate expression for the probability of blocking at the receiver side considering an acceptable QoS for a given minimum E2E delay. Given those constraints, we also develop an expression for the minimum number of channels that can provide us with that acceptable QoS value. Finally, we perform simulation measurements to validate our model. The results discussed the verifications of the analytical work against the associated simulation, to show a strong match between the analytical and simulation outcomes.
1.2 Contributions

The contributions of this thesis are summarized as follows.

1.2.1 Survey of the underwater wireless optical networks and communication systems

A thorough survey is provided about the challenges for video streaming in UWON with details on the previous methods and experimentations in UWOC. Those challenges include the fundamentals of the underwater channel characteristics, such as scattering, absorption, and turbulence. Understanding the causes of those impairments resulting from the inherent properties of the water medium itself and its effects on light waves. Other challenges related to building the video streaming system and integrating it into an optical setup as a network are also presented. Those may include hardware challenges to build a transmitter and a receiver, or software challenges that may include building the necessary packages that will perform the video transmission across all communication layers. In addition, the challenges associated with building the software packages to do the necessary system’s performance investigation for a fruitful analysis. Also, there are challenges that are not yet fully explored but are highlighted herein. The survey contain a complimentary background on the UWOC technologies, photonics, light, and underwater exploration and photography.

1.2.2 Underwater video streaming using point-to-point links

In this part of our work [9], the contributions are:

- **Design** an off-the-shelf, low power, cost effective, reconfigurable and real-time video streaming system. It is a video transmission system that enables the generation, coding, sending, transmitting through the underwater channel, receiving, and decoding of the live video streams. It represent a novel and practical ap-
plication specific experiment for the developments of underwater video related purposes.

- **Integrate** our system with the underwater wireless optical link that is offering Gigahertz (GHz) bandwidth. This include designing and setting up the appropriate laboratory optical testbed and the underwater channel physical characterisation as well.

- **Design** a novel online evaluation algorithm to measure the received videos BER to measure the system’s overall performance. This measurement system is built on software packages that we designed and implemented to demonstrate video streaming underwater and simultaneously measure the system’s BER.

- **Experimentally demonstrate** real-live video streaming using various modulation schemes over different ocean water types. The system is programmable such that modulation scheme, data packets, transmission power, and many other parameters are easily changed for an optimum performance. Other experiments are fixed into one modulation, one transmission power, etc., based on the hardware setup and allowances.

- **Evaluate** the system’s received video quality using extensive empirical results of the underwater live video streaming. The PSK and QAM modulation schemes that are evaluated over different ocean water types enable better utilization of the available spectrum. Many of the other experiments use On-Off Keying (OOK) intensity modulations. Our work demonstrates live video streaming is possible underwater with good quality and evaluates its quality based on more accurate and meaningful quality measurement metrics.

### 1.2.3 Underwater video streaming using bi-directional links

In the second part of our work [10], the contributions are:
• **Design** a **Bi-DIR** video streaming system for transmitting **UHD** resolution videos underwater. The downlink is used for video signals while the uplink is used for receiving feedback messages on the status of the underwater channel. This video transmission system enables the generation, coding, sending, transmitting through the underwater channel, receiving, and decoding of the live video streams. The systems design represent a novel and practical application for the developments of video streaming to assist the marine exploration vehicles to be fully autonomous. In addition to the observatory feature enabled through the video link, the feedback control messages are very essential not only in adapting the system’s throughput to the channel conditions, but also in controlling the movements of the vehicle in real time.

• **Design and Integrate** our system with the underwater wireless optical links that are offering **GHz** bandwidth. This includes the optimum design of the optical devices considering the two way communications setup where two Laser sources and two Photodetector receivers are to be aligned through optical lenses and reflection mirrors to provide the video downlink and feedback uplink channels while considering also the optimum path length required to properly perform the experiment in the limited laboratory configuration.

• **Design** the required online evaluation algorithm to measure and record the transmission throughput, the **Signal-to-Noise Ratio (SNR)** and the data link layer status by monitoring **Acknowledgments (ACKs)**. Also the received video quality was analysed using the **Peak Signal-to-Noise Ratio (PSNR)** metric and this measurement algorithm is built on software packages that we implemented off-line.

• **Experimentally demonstrate** **UHD** video streaming using higher orders and various **QAM** | **OFDM** modulation schemes over different ocean water types when
Bi-DIR communication links are established.

- **Evaluate** the system’s received video quality using extensive empirical results. Also evaluate the overall system’s performance using throughput analysis and the adaptive SNR metrics.

### 1.2.4 Underwater video transmission end-to-end delay analysis using multi-channels

In this work [11], we extend our contributions to analysing the E2E delay and probability of blocking when big data streams of videos are transmitted into a multi-channel underwater wireless optical configuration.

- **Analyze** delay-sensitive UWONs intended for live-video streaming applications. The video streams are generated at the sender side and are transmitted through underwater multi-channel paths that span over several meters of length, where the receiver is subject to a maximum E2E delay constraint.

- **Design** the system model and queue configuration for the multi-channel network based on the outcomes and lessons learned from the previous research on UWONs and our above experimental works.

- **Mathematically analyse** this network as an M/G/1 stochastic model to quantify the system’s delay performance and to obtain an approximate expression for the probability of blocking at the receiver side considering an acceptable QoS subject to a given E2E delay threshold.

- **Derive** and present an expression for the minimum number of channels that can support the video transmission given those constrains. We consider the system’s performance for a multi-channel system configuration.
- **Evaluate** and validate our model by using simulation and to demonstrate that the E2E delay and probability of blocking for several scenarios are in agreement with the model hypothesis.

The above experimental works provide the research communities with fundamental and substantial approaches towards programmable configurations that enable better spectrum utilization via using higher orders of modulation techniques that would have been very complex implementations otherwise. Those implementations enabled the demonstration of the highest quality video transmission ever achieved in UWON systems. Furthermore, the use of OFDM with up to 64-QAM modulation schemes provide the necessary platforms for streaming UHD video in such noisy underwater wireless channels. The Bi-DIR concept and configurations setup is demonstrated for the first time in UWON systems. Also the video E2E delay analysis in multi-channel configurations is mathematically modeled for the first time in UWON systems.

### 1.3 Thesis Outline

This thesis document is organised as follows. In chapter 2, we provide comprehensive background and state-of-the-art on UWON systems, concepts and implementations. In chapter 3, we present the real-time video transmission using UWON. Chapter 4 presents the UHD video transmission using Bi-DIR UWON. In chapter 5, we discuss the work on analysing the E2E video delays by mathematically deriving the associated formulas for multi-channel configurations. Finally, we present our conclusion in chapter 6 of this thesis and discuss our prospectus on future research directions.
Chapter 2

Background and developments

In the following sections, the thesis will include, to start with, an emphasis on underwater resources that motivate this research and other related community contributions in the field of underwater explorations. Following which is a historical background on light, optics, underwater photography, and underwater communication technologies. A subsequent section will introduce the fundamental theories of the light interactions with the water medium, and then go over the challenges to the UWOC implementations. The brief discussions on recent developments in UWOC systems will follow that next in order. The chapter will include a quick note on the status of underwater vehicles and one of their state-of-the-art developments.

2.1 Underwater resources

Before we look into the technology background and recent developments, a major motivation in pursuing this research is about the indispensable sources of life in the oceans that need to be explored, monitored and protected for future generations. We wish to look at some of those resources that are considered critical and vital for human existence and prosperity. For instance, the oceans have major sources for O\textsubscript{2} production and CO\textsubscript{2} fixation. Similar to land plants, Phytoplankton are mostly tiny single-celled photosynthetic species living suspended in water. They use the photosynthesis process to survive by converting carbon dioxide into oxygen and organic food. This constitutes to about half the Earth’s oxygen production, an asset worthy
of researchers credit [12,13].

Many other marine organisms are examples of sources for biotechnology-based applications, including natural products, such as flavours, fragrances, enzymes, and medicines [14]. The brine pools of the oceans, for instance, host a wide range of microbial gene communities, which are sources of enzyme for many pharmaceutical products [15], and some of them can be promising potentials for anti-cancer natural treatment. Also, tactical surveillance of the oceans is of interest to military, borders security, and rescue operations. Environment protection, disaster prediction, accurate weather predictions based on oceanic readings are of interest to many. Oil and gas on the other hand is yet to be discovered massively from the fields offshore, and then operated, inspected and maintained after completing its development [16].

Exploring and monitoring such resources with real-time video has huge potentials in serving many underwater applications. As when the situation entails critical, tactic and time sensitive operations, underwater systems need to be equipped with ultra-fast wireless communication solutions for the realization of live video streaming as an ultimate tool to virtually mimic the reality of that unseen environment. A current industrial major requirement comes from the oil and gas operations, for the inspection and maintenance of the huge network of subsea pipelines, cables and steel structures for the offshore oil and gas fields. Wireless solutions become essential alternatives for inspecting parts of those fields in shallow water, where large barges cannot approach near surface locations to carry a ROV. Current methods are difficult and costly as divers are constrained by the work hours and depths, and the accompanying boats remain costly to operate and subject to permissions of weather [17].

In order to facilitate such applications and gain better understanding of the ocean’s environment, it is of high importance to employ new concepts of communications systems with large bandwidths that realize live-video streaming in high-speeds and good quality from the underwater remote locations. Traditionally, marine ROVs are
used within very limited agility and manipulation abilities to examine and maneuver around the fragile coral reefs and biological specimens. This process can be dangerous, inadequate and harmful to the marine eco-system and deep sea environment if an accident happens while inspecting or repairing a network of oil and gas subsea pipeline or subsea communication cables \cite{18}.

2.2 From ancient civilizations to modern age

In this section, we take a glimpse at the various developments of the concepts and research related to light, optics, photography, and communications in the hope of making a collective and profound understanding of where this was and how underwater video transmission came about to what we have today and transmitting ultra-high definition video underwater as we present in this thesis.

2.2.1 History on light and optics research

Light has been used as a source for signaling messages throughout the ancient times and since earlier periods of times. Fire and smoke signals as basic forms of light were used to transmit messages. Metallic plates were polished to be used as mirrors in the Egyptian, Greek and Roman old times to reflect the light from the sun for long distance transmission of signals \cite{19,20}. The research on Optics was started by great philosophers in ancient Greece namely Socrates, Aristotle, Plato, and later by Euclid, who collected those fundamentals in his book ”Optics”, including reflection, diffusion and vision \cite{21}.

The inspirations and discoveries that had a huge impact on our world continued throughout the years through building upon knowledge of ancient civilisations. Until the golden time of the ”Father of modern Optics”, Al-Hasan Ibn al-Haytham, who contributed greatly in the field of light and optics and made us understand how we see things by light reflections on objects rather than barely from our eyes \cite{22}. Around
a one thousand years ago, by using the similarities between experimentation and theories he established the modern scientific methodologies of science and natural phenomena investigations. Among the numerous writings, his book the "Book of Optics" (Kitab Al–Manadhir), was translated in Latin as (De Aspectibus), which include experiments on light reflections and refraction on lenses and mirrors. The book also included his experimentation of building the Camera concepts as we know it today, by passing light through a tiny hole into a darkened room. In fact, the word camera came initially from the Arabic word (Qomrah) which means a small opening into a dark room, such as the airplane pilot cockpit and windows is called Qomrah, as it allows light through the small windows in front of the pilot. Those historic works made great influence on researchers in Europe and later throughout the world until today [23].

Followed by Galileo Galilei, in 1638, who tried to measure the speed of light with two observers having lanterns and shutters [24]. Also Roemer, in 1676, declared that the light travels with a finite and measurable speed. He used his observations of the solar system and Jupiter's moons to estimate the speed of light in an effort to make a better European maps [25]. In 1690, Christiaan Huygens wrote about the concept of light being a wave as the first mathematical theory of light propagation [26]. In England, Sir Isaac Newton, authored the book "Opticks" in 1704 and introduced the Light Particle Theory [27]. Thomas Young, in 1807, showed (Young's Experiment) for proofing his theory that light behaviour resembles a wave [28, 29]. Later in 1849, Armand Hippolyte Fizeau determined the speed of light to be 299,796 kilometers per second [30]. In 1864, James Clerk Maxwell established the foundation for modern electromagnetism through his Maxwell's Equations [31], until the time of Albert Einstein, the greatest physicist of the 20th century, who wrote in 1905 that the light is made of photons [32]. Following that, in 1920, Albert Michelson measured the speed of light in air and in vacuum [33]. It was until The International Committee
for Weights and Measures, in 1983, finalized the measurement of speed of light in vacuum to be exactly 299,792,458 metres per second [34].

For the interest of our work, the history of photons, light, communications, the research on optics, the camera concept and photography, the discovery of the underwater world may have only just begun.

2.2.2 Underwater exploration and photography

The first underwater exploration using photography devices was done by an Englishman by the name of William Thompson in Dorset in 1856. He covered his camera into a water proof housing and lowered it into the Weymouth Bay sea water while operating it from the sea surface on the boat [35]. Later in 1899, a Frenchman diver and photography pioneer Louis Marie Auguste Boutan produced the first official underwater photograph as a portrait of the Romanian oceanographer and biologist Emil Racovitza while he was diving wearing a suit with a hard hat. Boutan published a book about underwater photography [36], and later in 1893 he was a professor at the University of Paris marine biology lab when he invented the first underwater camera [37]. In 1952, a Scottish scientist Harvey Barnes introduced the concept of having an underwater television and published the first known scientific research about this in Nature [38].

2.2.3 Underwater acoustic communications

The underwater wireless communication solutions were introduced earlier by using acoustic systems. The earliest underwater acoustic systems were motivated by the submarines and underwater mines during the World War I times. In 1919, the first scientific work on underwater acoustics discussed the effects of ocean temperature and salinity changes on the refraction of sound waves [39]. Following which was the Japanese system that implemented 4-DPSK modulation with 20 kHz carrier frequency,
produced 16 Kbps to transmit an image of 256 x 240 pixels in 8 seconds, and to a range of 6,500 meters [40]. It was until 2000, when ASIMOV was initiated as a project for an autonomous underwater vehicle and an autonomous surface craft. Those vehicles remain in contact all the time and coordinate locations to operate the acoustic modems optimally when at vertical alignment. Two communication links were established, to transmit 400 bps using non-coherent modulation, and 30 Kbps with coherent modulation for higher speeds on the other link. The details on the hardware, equalization, synchronization and coding algorithms were provided [41]. In 2002, 128 Kbps signals were transmitted using an acoustic system in a shallow water environment. They implemented MPEG-4 compression standard to transmit 10 frames per second. It was intended for controlling the vehicle movement while inspecting 3000 meters deep underwater structures using a small autonomous underwater vehicle. The video signal is compressed and transmitted using acoustic waves to the AUV and from there to a repeater. To optimize the coverage range and provide higher transmission speeds that enable the video transfer, the AUV is accompanied by a ship that has an optical fiber cable suspended to the repeater which is located 300 meters above the sea floor [42]. In 2003, a new approach was implemented experimentally, which utilized video compression techniques and better modulation schemes. Data rates of 75, 100, 125 and 150 Kbps were achieved using 8-PSK, 16-QAM, 32-QAM and 64-QAM modulations, respectively. Combining the compression and modulation techniques was announced to enable real-time video transmission, and resolutions of still images were 144 x 176 pixels at a frame rate of 15 frames per second [43]. It is apparent that the achieved data rates with acoustic communications are yet very low even when using the highest modulation scheme.
2.2.4 Underwater optical communications

The invention of LASER (Light Amplification by Stimulated Emission of Radiation) which happened around the year 1959 when Gordon Gould published his work on the laser concept in a conference paper [44]. Regardless of the debate on who invented the laser [45], during those years from 1950s to 1970s, investigations of the use of underwater optical systems were undertaken by several researchers. The Radio Corporation of America, Aerospace Systems Division, at Burlington, Massachusetts, developed the U. S. Navy’s first underwater green laser [46] and was provided to aid the analysis. In 1971, submerged lasers underwater lighting was analysed in seven water types, and the result was put into a mathematical formula. The behaviour of the laser at different wavelengths and in different water types would be predicted using the equations and computational tools. The objective of the study is to measure the optical constants of water and assess the techniques required for underwater photography utilizing the regular light sources [47]. Several other investigations were undertaken to develop the required models for the optical propagation of light in ocean water. In 1976, the measurement devices that can estimate the light effects on underwater imaging was developed [48]. Light reflectance and water physical and optical properties were also discussed [49].

Those models were useful in analysing the communication for wireless optical applications such as submarine links to satellites [50]. In 1976, the communications channel linking underwater and a satellite was characterized using a scattering model. The interface between air and water was considered in the study. The water absorption was shown to be the dominant factor in the losses as presented in the radiance function. The scattering losses can be minimized when separated from the absorption by imbedding the receiver in the water. Moderate transmission rates were foreseen to be achieved using such links [51]. Also, the use of laser for underwater communications was investigated after the invention of laser in 1950s [52]. A prelimi-
nary system design was presented in [53] for the growing interest in the deployments of blue and green optical spectrum to establish laser communication links between underwater submarines and satellites. Those designs were not taken into practical implementations as further developments are still required in the laser technologies.

It was until the beginning of the 2000s, when further developments in the visible light were achieved in the laser and high power LEDs technologies and that promoted their use for bandwidth demanding wireless communication applications. The luminescence measurement system was advanced to include 28$mW/cm^2$ (470 nm) blue LEDs, 400$mW/cm^2$ (839 nm) infrared laser diode, and (532 nm) green laser [54]. The same development also promoted the use of these technologies for underwater communications.

Further studies promoted the wireless applications between new concepts of underwater vehicles such as AUVs and ROVs. The analysis of underwater optical behaviour in the forms of signal attenuation and physical properties of fundamental interactions between light and water was investigated in various locations such as the Yellow Sea, Arabian Gulf, and East China Sea. The studies considered the depth variations effects on underwater communications with more emphasis on locations that are close to the sea bottom and surface. The variability in the water vertical column is key in evaluating the optical signal strength and thus to assess the performance of the underwater wireless optical communication systems [55,56].

Although the underwater autonomous vehicles technologies have made significant improvements throughout the past decade, underwater wireless optical communication technologies still lag behind where bandwidth capacities and coverage ranges are still posing serious challenges. For this reason, the acoustic technologies are still the most commonly used form of communications underwater. Despite the challenges, Sonardyne which was established by John Partridge in 1971, have diversified their businesses to do research programs and manufacturing of underwater wireless opti-
cal communication devices \cite{57}. Further developments that happened in the recent years are introduces in the subsequent section after discussing the challenges in the following section.

2.3 Challenges to underwater communications

Current optical communication technologies offer high capacity links with low latency for next generation underwater applications and that is in the favour of implementing the delay sensitive applications that are based on live-video streaming. However, unlike Free-Space Optical (FSO) links on air, UWOC systems are heavily affected by several optical properties of oceans water which pause extreme challenges \cite{58, 60}.

This section is to introduce the various properties of water that can determine the communication system’s behaviour when using light sources to carry the communications signal underwater. The underwater channel impairments are identified and discussed. There are mainly inherent properties that describe the optical characteristics of the water as a communication’s transmission medium. On the other hand, there are also the apparent properties of ocean water that in addition to the water medium will consider the designs of the light sources and receivers \cite{61}.

2.3.1 Light wave interactions with water

In general, electromagnetic theory explains well the transfer of energy that happens when light is propagating in the medium as an electromagnetic wave. The wave properties such as wavelength and frequency will be present when discussing light characteristics and behaviour. In principle, and coming back to the speed of light in vacuum that we mentioned earlier, the light wave propagates at a speed $V$ which is related to the wavelength $\lambda$ and wave frequency $f$ by the following.

$$V = \lambda \cdot f$$  \hfill (2.1)
The symbol $V$ is used here to denote the speed of light, which was used initially by Maxwell (around 1856) and Einstein (around 1905). It is used here rather than the commonly used symbol $c$, not to confuse it with the total attenuation coefficient $c(\lambda)$ that we will introduce shortly below in Eq. 2.7. Hence, that this is not always the case with the speed of light, as light wave propagates differently in different mediums, and its speed will be reduced by a value known as the refractive index. The water medium, being the subject of our research, has a refractive index of around 1.33, while this value comes in variations depending on the salinity differences in ocean water types, among many other factors. When light is incident on the water volume it experiences losses of its energy in terms of the received number of photons; best known as attenuation. Part of the light photons will pass the water volume and propagate all the way to the other end, another part of the light photons will be reflected either partially or fully, and the third part will be diffused into the water medium and change the photons status by interacting with either the dissolved or suspended materials that make the contents of the water medium. Those phenomena are known as absorption and scattering and we will come to know more details about them in the following subsections.

The energy conservation states that the incident light energy, best know as radiant flux which is wavelength dependent, and when transmitted through the water channel with energy $\phi_T$, is equal to the summation of the energy of light photons that pass through the water and received fully at the other end $\phi_R$, the energy of the absorbed light photons that is diffused into the water contents $\phi_A$, and the energy of the scattered light photons that is reflected $\phi_S$ by the contents of the water volume.

$$\phi_T(\lambda) = \phi_R(\lambda) + \phi_A(\lambda) + \phi_S(\lambda) \tag{2.2}$$

From this equation we can deduce the absorbance, which is the ratio of the absorbed energy to the transmitted energy.
\[ A(\lambda) = \frac{\phi_A(\lambda)}{\phi_T(\lambda)} \]  

(2.3)

Also, the scatterance is deduced to be the ratio of the scattered energy to the transmitted energy.

\[ B(\lambda) = \frac{\phi_B(\lambda)}{\phi_T(\lambda)} \]  

(2.4)

When the light beam passes through a unit length \( l \) of the water medium, the absorption coefficient is represented as follows.

\[ a(\lambda) = \lim_{\Delta l \to 0} \frac{\Delta A(\lambda)}{\Delta l} = \frac{\delta A(\lambda)}{\delta l} \]  

(2.5)

The scattering coefficient is represented as follows.

\[ b(\lambda) = \lim_{\Delta l \to 0} \frac{\Delta B(\lambda)}{\Delta l} = \frac{\delta B(\lambda)}{\delta l} \]  

(2.6)

The total attenuation coefficient is the summation of the absorption and scattering coefficients.

\[ c(\lambda) = a(\lambda) + b(\lambda) \]  

(2.7)

We will find those coefficients later in this thesis to identify the optical clarity of the water channel and to describe the amount of attenuation the light beam experiences when passing through different types of ocean’s water. It can be looked at as the amount of noise a communications signal is exposed to when passing through different underwater channels.

When the light beam travels \( l \) meters into the water channel, the amount of losses (negative gain) in the photons energy per unit length can be expressed as follows.

\[ - \Delta \phi = \phi_A + \phi_S \]  

(2.8)
This is expressed in terms of the total attenuation coefficient and over \( l \) meters as follows.

\[
- \Delta \phi = c \cdot \phi(l) \cdot \Delta l
\]  

(2.9)

The total losses over the whole communications path with length \( l \) is obtained by integrating (2.9) as follows.

\[
\int_0^l -\Delta \phi \cdot dl = \int_0^l c \cdot \phi(l) \cdot \Delta l \cdot dl
\]  

(2.10)

Simplifying further (2.10),

\[
\int_0^l \Delta \phi \cdot dl = -c \cdot l \cdot \int_0^l \phi(l) \cdot dl
\]  

(2.11)

Finally, we find the total losses caused by absorption and scattering to be as follows.

\[
\phi(l) = \phi_0 \cdot e^{-c \cdot l}
\]  

(2.12)

This formula in (2.12) represents the classical Beer-Lambert law, which forms the basic approach for estimating the losses in the communications signal when propagating through a specified path length. As we will be discussing systems’ implementations in this thesis, we find it more appropriate to express this formula in terms of the received optical power \( P_R \) (Intensity at the receiver) and initial optical power \( P_0 \) (Intensity at the transmitter), as follows.

\[
P_R(l) = P_0 \cdot e^{-c \cdot l}
\]  

(2.13)

Noting that Beer’s formula is only valid when the scattering coefficient \( b(\lambda) \) is insignificant, but when the communication’s signal is transmitted in a highly attenuated ocean’s water such as in turbid waters or over long distances, a multi-scattering of light photons can cause them to return into the original light beam until they arrive
to the receiver field of view FOV. It is therefore more appropriate to express the attenuation coefficient $c$ in the Beer’s formula in terms of the scattering albedo, defined as the ratio of the scattering coefficient to the total attenuation coefficient.

$$\omega_0(\lambda) = \frac{b(\lambda)}{c(\lambda)}$$ (2.14)

The modified Beer’s law becomes as follows.

$$P_R(l) = P_0 \cdot e^{-(1-\eta\omega_0)c\cdot l}$$ (2.15)

where the scattering factor is $0 \leq \eta \leq 1$. When These formulas are used to model more complex light propagation underwater to cover the other impairing phenomena other than scattering and absorption, then the analysis becomes more sophisticated and other models are needed. We will start in the following subsections to introduce the main causes of the scattering and absorption of light in the underwater environments.

### 2.3.2 Scattering and absorption

Scattering and absorption of light are two main causes of degradation of UWOC performance for long range transmissions and high quality imaging systems. Many factors form the fundamentals of interactions between light and water. The water, being the signal transmission medium, itself absorbs differently the light from each wavelength of the light spectrum and has clear scattering behaviour against the randomly varying refractive index. A more significant optical element when it comes to oceans water is the natural existence of marine life as either dissolved or suspended particles. This constitute to the turbidity of the ocean water that defines the degree of its optical clarity. Particulate Organic Matter (POM) such as phytoplankton, zooplankton, and detritus, contributes to scattering and absorption of light. Dissolved Organic Matters (DOM) such as carbohydrate, saccharide, and humic acid,
contribute to absorption only. **Particulate Inorganic Matters (PIM)** such as eroded soil from rivers and dust blown from the main land, contribute to light scattering only; best known as Mie scattering phenomena \[63,64\].

### 2.3.3 Turbulence

Turbulence on the other hand, resulting from varying dissipation rates of temperature and changing salinity, also play a major role in the degradation of the optical signal in oceans. Any small changes in salt concentrations can result in salinity variations and subsequently more fluctuations of the refractive index. This optical turbulence may heavily attenuate the image quality received from **UWON** systems \[65,66\]. Moreover, ocean water is blue due to the Rayleigh scattering phenomena, as when the sunlight penetrates into the deep water, the blue and green spectrum region is absorbed the least and therefore can propagate into longer depths up to a kilometer range from the surface. This constitutes to higher levels of ambient interference to the optical communications signal that cannot be avoided during daylight hours \[67\].

### 2.3.4 Air bubbles

When air bubbles are formed in the ocean’s water, they form a significant change to the light scattering as well. As the fundamental light interactions with bubbles underwater, it either gets refracted or reflected to another direction at the point where water and air intersect \[61\]. Forming a good understanding of this interaction is key in designing an optimal **UWON** system for a better video transmission underwater. The rain and the surface waves movement and when breaking can generate different sizes of the air bubbles, which are ongoing processes that can not be avoided while streaming live video underwater. An experimental investigation of the effects of air bubbles on the statistical distribution of intensity for underwater wireless optical channels under different channel conditions. It was shown that the salinity variants
can attenuate the received signal power while major fluctuations in the intensity are caused by the air bubbles presences [68]. Another experimental study on the effects of different air bubble sizes and amounts has been performed in [69] to assess the performance of UWOCs systems. Statistical distributions have been approximated to represent the models as part of the outcomes of those experiments.

2.3.5 Existing communication limitations

Existing technologies such as acoustic communication are widely deployed underwater but are generally limited by their low data rates (in Kilobit per second (Kbps)) not sufficient for real-time and good quality video streaming [70]. The Radio Frequency (RF) waves are also not suitable as they become strongly attenuated underwater [18]. Low frequencies (300 Hertz (Hz)) may propagate underwater but require large antenna and consume high transmission power [71]. As a promising alternative, UWOC offers much higher bandwidth enough to stream live video. In addition, due to the ease of deployment, low power consumption, much faster data rates, and increased security, UWOC is becoming a preferred option. Nevertheless, it has also its own challenges and is still in its infancy.

2.4 Recent developments on underwater wireless optical networks

The research in underwater wireless optical communication was motivated by the advancements made in the visible light communications for air applications. The possibility of using visible light for underwater communication applications followed that of free space air communications. Free-Space Optical communications was reviewed for broadband networks and back-haul applications over long and short ranges up to kilometers distance. In 1995, a five years research plan was undertaken to evaluate the optical system’s capacities, policies, power consumption, effects of weather
on attenuations, and implementation costs [72]. The investigation of modulating and encoding the visible light generated from Light emitting diodes (LEDs) to transmit audio signals or lighting that can be used for signaling such as in traffic management or for divers communications, was constructed experimentally. A line-of-sight 20 meters range was achieved in transmitting an audio signal through a traffic light LED, and implementing an intensity modulation and direct detection technique [73].

2.4.1 Underwater wireless optical communications

However, as UWOC is an emerging technology that has gained a considerable interest from several research communities in the very recent years. Also, as the optics and laser technologies are advancing to provide higher bandwidth and transmission speeds at Gigabit per second (Gbps) UWOC is considered as an attractive alternative to the existing conventional, low bandwidth, and high propagation delay underwater communication systems (i.e. acoustics and RF systems) [18,70].

UWOC systems provide the potential for those envisioned underwater vehicles and sensor nodes to gather and send huge amount of information in a short period of time much less than what the current conventional underwater acoustic communications can support [74]. A larger variety of underwater applications such as oceanography and imaging, real-time video streaming, high throughput Underwater Wireless Sensor Networks (UWSN) can be exploited using UWOC. Several benefits rely on the high data rates, low latency, and low power consumption that make it more attractive alternative to establish networks between ROVs and UWSN to retrieve, offload, download or exchange larger sets of data in real-time while minimizing energy loss and traffic congestions [75].

Recent developments in UWOC systems were demonstrated in several experiments such as in [76–80], and achieved up to 16 Gbps where their major themes were to achieve the highest data rate possible. The higher transmission rates are obtained by
deploying advanced modulation formats, such as OFDM, which when implemented together with high-orders of QAM can greatly improve the spectral efficiency of the underwater video transmission system. Moreover, employing QAM-OFDM modulation and directly modulated lasers provide symbol and power efficient loading for different sub-carriers to improve the communication performance. Implementations of OFDM modulation for UWOC experiments have been carried out using either green lasers or blue lasers as in [81,82]. However, the dominant impairing phenomena of underwater absorption, scattering, and turbulence continue to degrade heavily the performance of underwater video transmission systems [66,83] and prevent developments of long range UWOC links.

Previous theoretical and experimental work have been carried out for exploring the behavior of optical signals underwater, examples of recent projects include [77, 78, 84–86]. Although Gbps speeds were achieved, the aforementioned constrains can confine the existing implementations within moderate ranges of few meters for UWOC. Underwater absorption, scattering, and turbulence are the key factors that significantly affect the performance of UWOC links and image-quality of underwater video and imaging systems [62, 66, 68]. As a matter of fact, only short range links have been established for UWOC [77,78,84–86].

2.4.2 Limitations on video transmission underwater

The research on underwater video transmission has been sparse and only few studies have been reported. In 2005, Chancey established a 10 Mbps UWOC based video link over 4.6 m clear water channel [5]. In 2007, Baiden et al. [6] also constructed a 10 Mbps untethered telerobotic system to transmit video information underwater over a 10 m range on Long Lake in Sudbury, Ontario. The AquaOptical II video transmission system device [7] was based on an array of 18 LEDs transmitter and has a bandwidth limit of 4 Mbps. Moreover, a UWOC video system with externally
modulated data in a varying water tank visibility was demonstrated in [8]. Those aforementioned research projects have established and shown the feasibility of underwater video streaming. However, those studies did not provide a systematic analysis to investigate the effects of various underwater channel conditions, resulting from changing the water turbidity levels, on video quality and when different modulation techniques are used.

2.4.3 Multi-channel links for underwater wireless optical communications

In general, and not necessarily intended for video streaming, several techniques have been proposed to overcome the short range limitations by exploring the spatial diversity and multipath channels in [UWOC] systems. For example, performance studies for multi-channel systems, [OFDM] and spatial modulation techniques. Also, cooperative relaying diversity as in Jamali et al. [87] who presented performance analysis of [UWOC] system using [Optical Code Division Multiple Access (OCDMA)] and [Optical Orthogonal Code (OOC)] over turbulent channels. Multi-hop links were considered to the receiver through a relay-assisted [Point-to-Point (P2P)] [UWOC] system. A dual-hop transmission in a 90 [m] P2P clear ocean link achieved 32 [Decibels (dB)] gain while [BER] was $10^{-6}$. Another example of a study for relay based [UWOC] is introduced in [88]. [RF] multi-channel scheme was also proposed, although [RF] waves experience significant losses as a result of higher conductivity of ocean water. Kulhandjian [89] reported that an advantage in [RF] communication can be gained from using multi-channel schemes. It was reported that using [QPSK] modulation scheme over four transmit antennas achieved 48 [Kbps] at 23 [Kilohertz (kHz)] bandwidth over a 2 [Kilometers (Km)] link. This link is not suitable for video streaming for its very low bandwidth regardless of the achieved long range transmission. The potential of implementing multi-channel system has been investigated by various [UWOC] research
groups covering many aspects. Multi-channel system’s performance considering pointing and alignment was evaluated in [90], together with channel capacity of downlink UWOC based multi-channel systems. A random sea surface slope model was used to find the pointing error resulting from small jitter of the transceivers for a vertical buoy-based UWOC system. They show for highly turbid water, longer link ranges, and higher inter-spacing that the channel capacity decreases. Multi-channel system modeling of aquatic optical attenuation for Line-of-Sight (LOS) configurations was considered by Dong et al. in [91]. They derived a closed form expression for the impulse response of a 2x2 channels UWOC system using weighted double Gamma functions in turbid water channels. Multi-channel system performance for the design of modulators for UWOC was presented by Jamali et al. in [68], to reduce the effects of turbulence when using OOK modulation.

On the contrary to the single-channel systems, multi-channel configurations for UWOC systems provide higher power efficiency, higher reliability and resilience to turbulence, and higher capacities [92], [93]. Additional complexity in the design of the system when adding multi-channel schemes limits its experimental implementations. Adequate designs for such transceiver configurations is still a potential for future research [92]. Also, those research efforts have paid less attention to looking into the queueing associated delays in UWOC the subsequent packet dropping, and setting the minimum acceptable QoS metric for the received live-video packets. Nevertheless, achieving higher transmission ranges increases absorption and loss probability, scattering generates more Inter-Symbol Interference (ISI), and turbulence induces fading, yet we believe using multi-channel spatial diversity can achieve better gains when transmitting multiple copies of the same information through different independent and identically distributed fading channels which may increase the probability of receiving a decodable and good quality video packet.
2.5 Underwater vehicles

One of the most advanced and latest ROVs is OceanOne developed by Stanford and KASUT [94]. Yet, to make those ROVs more interactive with ocean surroundings, and meet many challenges when accessing oceans deep, it is imperative to make those ROVs fully autonomous when enabled with an ultra-fast wireless connections integrated into their robotic intelligence, sensing capabilities, and vision acquisition techniques all together. In order to virtually mimic the human intuition and cognition in real time, and safely perform well in those locations that are unsafe for divers, ROVs must be equipped with state-of-the-art communication technologies that enable underwater real-time video capabilities and provide wireless feedback control links for immediate navigation commands.

2.6 Discussion

In this chapter, we provided a quick overview of the underwater resources, to show the importance of the oceans in providing us with the vital lifeblood that will enrich us and our future generations with immense resources necessary for our and their existence. This great motivation of our work empowers us to do the impossible and enables us to move to the next section. In the background and historical part of the chapter, we took a look at the beginning of ancient human generations and how they perceived the light phenomena and the energy forms of the light. We provided a quick overview of the transfer of knowledge and ideas from the different cultures and civilizations, to the golden time of the father of modern optics, to the twentieth century and modern age technological revolutions. We have then looked at the initial trials of human exploration to the underwater world using photography in its basic format. After that we surveyed the beginning of using wireless communications in the form of sound waves and the developments of the acoustic systems until
the laser devices were introduced. The conceptual use of optical communications for underwater applications was briefly introduced. A following section discussed the challenges to the underwater wireless optical communications. It included an introduction about the light wave interactions with the water being the communications medium. The scattering and absorption were discussed being the dominant impairment sources to the underwater optical channels. We also discussed the turbulence as a result of temperature and salinity variations, and the water bubbles effects on the communications signals. The limitations to the other wireless technologies were then discussed. It was the time to move to the developments and recent state-of-the-art systems, while keeping in mind our objective is to improve on the video transmission and receiving quality and overall system’s performance. We therefore talked about the related work on underwater video transmission, what was achieved, and what is to be improved. We also discussed the limitations on the analysis of a multi-channel configuration that can be considered as a candidate solution to enhance the reliability of the underwater transmission systems. At the end, we introduced the latest and most advanced underwater vehicle an emphasized on the point that motivates our work, which is enabling those vehicles to move freely when equipped with wireless solutions and video transmission capabilities.

In the next chapter, we will introduce our first approach in transmitting a real-time and good quality underwater video. This includes the details of the reconfigurable Software Defined Radio concept and the system’s design. Also the experimental setup and system’s specifications, the evaluation methodology, codes and algorithms. At the end of the chapter comprehensive results are provided and analysed.
Chapter 3

Real-time video transmission in underwater wireless optical networks

In this work [9], we evaluate the performance of a low-power, cost-effective, and UWOC based real-time video system employing QAM and PSK modulations. We take into account various underwater channel link conditions and analyze both overall BER and video quality. Performance results reveal that live video streaming is not only feasible over different ocean water types but also with good image quality.

3.1 System model

The video streaming system is built on Universal Software Radio Peripheral-Reconfigurable Input/Output (USRP-RIO). LabVIEW software interface allows users to reconfigure and operate this hardware to suit our desired video application. When live video streams are captured via a DirectShow compliant webcam, the acquisition attributes are configured through NI-MAX software for the recommended resolution of 320 x 240 pixels. NI Vision Acquisition performs the various media processes, from detecting the camera, opening the camera session, to fetching the video streams from the camera into the host PC. The video streaming bits are assembled in 128 bit-message length, and built into packets with 30 guard bits, followed by 30 synchronization bits, the 128 message bits, and ending with 70 pad bits. Fig. 3.1 shows the video packet size and structure.

The packets are then modulated and transmitted by one
dio Peripherals (USRP) device into the laser diode through the underwater channel. When the packets are received by the photodetector then arrive into the second USRP receiver, they go under resampling and matched filter, demodulation, and detection of synchronization bits. The video packets are then displayed on the host PC. This digital communications model is shown in Fig. 3.2.

![Digital communications model for the transmitter and the receiver.](image)

**Figure 3.2** Digital communications model for the transmitter and the receiver.

### 3.2 Experimental setup

The actual photograph of the underwater real-time video transmission system setup is shown in Fig. 3.2. We utilize a 15 mW commercially available, TO-9 packaged and single-mode fiber-pigtailed green Laser Diode (LD) (Thorlabs LP520-SF15) as the optical transmitter.

Fig. 3.4 presents the light-current-voltage (L-I-V) curves of the pigtailed green LD having a threshold current of 58 mA, and a slope efficiency of around 16.7%. Fig. 3.5 shows the emission spectra of the LD under different injection currents obtained using a high-resolution spectrometer (Ocean Optics HR4000). The Full-Width at Half-Maximum (FWHM) of the LD is 0.45 Nanometers (nm). The emission center
Figure 3.3: Actual photograph of the water tank showing: (a) laser driver mount, (b) collimator lens, (c) attenuator, (d) green laser beams, (e) mirrors, (f) mirrors, (g) focusing lens, (h) avalanche photodiode (APD).
wavelength at 70 mA is around 515.2 nm and slightly changes with increasing injection current.

Figure 3.4: Characteristics of the 520 nm LD at 25°C: L-I-V curves.

The video packets from the first USRP transmitter were superimposed on the DC laser bias current using the built-in Bias-Tee RF input within the laser driver mount (Thorlabs LDM9LP). The output radiation of the LD was collimated by a plano-convex lens (Thorlabs LA1951-A) of 25.4 mm diameter and 25.4 mm focal length to produce a parallel beam which is incident on the underwater channel. The underwater channel was simulated using a water tank made of Polyvinyl Chloride (PVC) with 1 x 0.6 x 0.6 m³ dimensions. The tank was filled with municipality fresh tap water with an estimated attenuation coefficient = 0.071 m⁻¹ [56], which is similar to the clear blue ocean water type. The optical path length in the water tank was
Figure 3.5: Characteristics of the 520 nm LD at 25°C: optical spectra with increasing bias currents.
extended up to 5 m using mirrors installed at both ends of the tank. After propagating through the water tank, the optical beam was focused into a high sensitivity silicon Avalanche Photodiode (APD) (Menlo Systems APD210) receiver unit using a 75 mm focal length lens (Thorlabs LA1608-A). The APD has 1 GHz cut-off bandwidth, 0.5 mm active diameter, 0.4 pW/Hz\(^{1/2}\) Noise Equivalent Power (NEP) and around 13 A/W responsivity at 520 nm. The video signal is finally received by the second USRP receiver for interface and processing by the host PC through a PCI-E x 4 Gbps cables.

Figure 3.6: Schematics of the underwater video streaming system over a reconfigurable wireless optical link. SMA: SubMiniature version A connectors, SDR: Software Defined Radio.

Fig. 4.5 depicts the schematics of the overall system. All measurements were taken under normal room illumination conditions. The water turbidity level is changed by adding accurate Maalox solution based on [95] in an orderly fashion, in order to simulate various underwater channels as in Table 3.1. The amounts of Maalox
concentration added to achieve the desired absorption and scattering coefficients corresponding to the clear, coastal, harbor I and harbor II water types, respectively, are shown in the last column of Table 3.1 and is based on [96]. After the addition of each Maalox concentration, we sufficiently stirred the mixture to obtain a uniform water channel before proceeding with the measurements.

Table 3.1: Representative absorption, scattering and total attenuation coefficients

<table>
<thead>
<tr>
<th>Water Type</th>
<th>a (m$^{-1}$)</th>
<th>b (m$^{-1}$)</th>
<th>c (m$^{-1}$)</th>
<th>V(µL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear water</td>
<td>0.114</td>
<td>0.037</td>
<td>0.151</td>
<td>29.2</td>
</tr>
<tr>
<td>Coastal water</td>
<td>0.179</td>
<td>0.219</td>
<td>0.398</td>
<td>75.6</td>
</tr>
<tr>
<td>Harbor I water</td>
<td>0.187</td>
<td>0.913</td>
<td>1.10</td>
<td>198.1</td>
</tr>
<tr>
<td>Harbor II water</td>
<td>0.366</td>
<td>1.824</td>
<td>2.19</td>
<td>383.6</td>
</tr>
</tbody>
</table>

### 3.3 Bit error rate calculation

The overall system performance is evaluated using the measured BER. It is the ratio of the number of erroneous bits to the number of true bits following a trigger in the current input bit stream which is the Synch bits in our case. This measurement is implemented using software packages that are based on 100K samples from the output of the MT Calculate BER after Trigger (PN Sequence) library [97], as shown in Fig. 3.7. Using software simplifies the design and replaces expensive and complex hardware commonly used for underwater wireless optical systems experiments such as J-BERT (Bit Error Rate Tester).

The average BER is calculated against a Galois PN Sequence generated in the receiver side. The sequence must be the same as the PN sequence generated by MT Generate Bits (Galois, PN Order) in the transmitter side and with a matching PN order. All subsequent iterations of this node use a continuation of the same PN sequence until (reset?) input becomes TRUE. If this function is called for the first
time or whenever (reset?) is TRUE, the node begins a blind search over the input bit stream for a (trigger found?) index location in which the BER of a number of subsequent bits is below the specified BER trigger threshold. The confidence input value specifies the number of bits after the trigger found index which are to be used in the trigger threshold calculation. The bit sequence over which BER is calculated is known as input bit stream. This bit stream must include only data bits of the PN sequence. The minimum number of input bits required to return a meaningful BER value is given by Eq. 3.1

\[
N_{\text{min}} = \text{int}\left( \sqrt{y \times \text{threshold} \times (1 - \text{threshold})} + 120 \times \text{threshold} + \sqrt{y \times \text{threshold} \times (1 - \text{threshold})} \right)^2
\]  

(3.1)

Where y is defined such that confidence = \(P(x \leq y)\), and x is a zero-mean, unit-variance Gaussian variate. \(P(x \leq y)\) denotes the probability that the variable x takes a value that is less than or equal to y.

### 3.3.1 Synch bits detection and matching BER trigger

To detect the Synch bits in the LabVIEW video streaming package, we develop Algorithm 3.11. The PN sequence order takes values from 5 to 31, inclusive. The BER trigger threshold takes values 0.0 to 1.0, inclusive. We show the ranges of required input length for a BER trigger threshold input in the range [0.1,0.5] as in Fig. 3.8 and a confidence input in the range [0.5,0.99] as in Fig. 3.9. We modify this design by
specifying a confidence value of (-1) to allow triggering on input bit stream lengths equal to \((3 \times \text{PN sequence order})\). As the input bit stream is the Synch bits (30 bits), we choose PN sequence order in our setup = 9, also the BER trigger threshold = 0.496 and confidence = -1, as shown in the BER detection block diagram 3.10. This design results in a seamless video transmission and activates BER calculation as well.

Figure 3.8: BER threshold graph.
Figure 3.9: BER confidence graph.
3.3.2 BER moving average calculations

As BER results found from implementing Algorithm 3.11 are executed for each packet in a very fast fashion that is hard to be tracked or recorded for post analysis. The underwater channel conditions vary intermittently as well resulting in continuously varying BER values. Therefore, we design Algorithm 3.12 for implementation in LabVIEW to calculate the average BER based on 100K samples of the resulting BERs. This novel algorithm designs enabled us to efficiently perform an accurate evaluation. The LabVIEW code implementation to calculate the BER is shown in the block diagram, as in Fig. 3.13.

3.4 Experimental results and discussions

In this section, we present comprehensive analysis on the visual aspects of the received video quality as well as quantitative measures on both the overall system’s performance and the video quality.
Algorithm: 3.11

Generate Synch bits at Tx (PN sequence order);
Generate Synch bits at Rx (PN sequence order);

for each incoming packet do
    if each Synch bit matches up then
        Return TRUE;
        Add packets to the output;
    end
    if each Synch bit not matching then
        Return FALSE;
        Do not send packets;
    end
end

Strip Synch bits from Demodulated bit stream;
Input Synch bits into MT Calculate BER function;

for Synch bits input and PN sequence order = 9 do
    if Synch bits length > $3 \times PN$ sequence order then
        Calculate BER;
    end
    if Synch bits length < $3 \times PN$ sequence order then
        Do not calculate BER;
    end
end

Figure 3.11: Synch bits detection and BER trigger threshold
Algorithm: 3.12

while valid packets are received do
    Create file to record all resultant BER values for future reference;
    Create new file for writing BER averages;
    while accumulate BER value is valid input do
        Set X (maximum number of BER values);
        /* X is the number of samples = 100K */
        if current iteration < X then
            /* the maximum number of BER samples is not reached yet */
            for N=1, ∞, i++ do
                Add Accumulated BERs;
            end
        end
        if current iteration > X then
            /* the maximum number of BER samples is reached */
            /* calculate the BER average based on the 100K samples */
            BER average over X samples = the total sum divided by X;
        end
    end
    Write BER average values into file;
    Draw BER averages Chart;
end

Figure 3.12: Average BER calculation

Figure 3.13: Block Diagram of BER calculation in LabVIEW.
3.4.1 Visual analysis

In this subsection we are presenting the visual analysis part of the study. Fig. 3.14 shows the eye diagrams, constellation maps, and received video images for clear water channel conditions under 8-PSK modulation and Fig. 3.15 for 8-QAM modulation. For simplicity, we show representative samples of the results. We observe that the eye diagrams are open for both modulations. The constellation maps are fairly distinguishable and we observe clear images.

Figure 3.14: Clear water: (8-PSK) (a) eye diagram, (b) constellation graph, (c) transmitted video, (d) received video.

Figure 3.15: Clear water: (8-QAM) (a) eye diagram, (b) constellation graph, (c) transmitted video, (d) received video.

We further investigated video transmission in coastal and harbor I waters. We found that the eye diagrams and constellation maps for each modulation were similar to clear water channel conditions. In Fig. 3.16 we present transmitted and received video images for 8-PSK and 8-QAM modulations for coastal water. We also show the results for harbor I in Fig. 3.17 for both 8-PSK and 8-QAM modulations. High quality
and colored videos were obtained for both coastal and harbor I waters. However, there is a little distortion that is hardly noticed only when using 8-QAM at the right bottom corner of Fig. 3.16(b). It is corrected immediately and seamlessly on the next packet retransmission. This is an indication that 8-PSK suffers the most and this fact prevails in the next findings while we increase water turbidity as in harbor II.

![Figure 3.16: Coastal water: (a) transmitted video; received videos for: (b) 8-PSK, (c) 8-QAM.](image)

Finally, we studied video transmission quality in highly turbid harbor II water. Fig. 3.18 illustrates the received images next to the transmitted image for all modulations. As seen in Fig. 3.18(b), 8-PSK on harbor II ocean water type suffers the most. Fig. 3.18(c) shows that the received video also suffers from minor distortion at the bottom with 8-QAM but is still better than 8-PSK. Although these are intermittent
results and videos become clear again using retransmissions, but for the sake of completeness, we thought it provides an idea about the performance of the system at the most turbid water (i.e. harbor II).

![Image](image1.png)

Figure 3.18: Harbor II water: (a) transmitted video; received videos for: (b) 8-PSK, (c) 8-QAM.

When we go from clear water to harbor II, the turbidity increases and the optical signal gets significantly absorbed and scattered. In the case of 8\textsuperscript{QAM} modulation scheme the constellation regions on the complex plane are larger and the boundaries are looser. Hence, it outperforms 8\textsuperscript{PSK} as the probability that one constellation point falls into the adjacent region or incorrect boundary is higher for 8\textsuperscript{PSK}; especially when the channel attenuation is very high as in the case of harbor II. Another advantage of using higher orders of \textsuperscript{QAM} is that it is able to carry more bits of information per symbol but is less resilient to higher noise. As shown in Fig. 3.18, the video color, quality and the resolution are not significantly affected by the increased turbidity of the water. Note however that the water channel may have visual influences on the colored video when the link distances increase to longer ranges \cite{98}.

### 3.4.2 Bit error rate analysis

To evaluate the overall performance of the video transmission system, we present the average \textsuperscript{BER} in Fig. 3.19. The \textsuperscript{BER} increases with turbidity of the water, however the increase is evident when transmitting video in the most turbid harbor II water.
Here we can see that all modulations achieved $1.0 \times 10^{-9}$ BER except for 8-PSK which resulted in $[1.43, 3.9, 4.3, \text{ and } 9.9] \times 10^{-9}$ in clear, coastal, harbor I, and harbor II, respectively.

![Figure 3.19: BER of received videos.](image)

### 3.4.3 Video quality SSIM analysis

In order to quantitatively assess the effects of using different water types and modulations on the received video quality, we use Structural Similarity (SSIM) method for quality analysis of the received video images based on the work of [99]. This quality metric assesses the visual impacts of luminance, contrast and structure of an image. Eq. (3.2) shows a multiplicative combination of the three aspects.

$$SSIM(xy) = [l(x, y)]^a + [c(x, y)]^b + [s(x, y)]^y$$  \(3.2\)
The luminance effects are calculated using local means, standard deviations, and cross-covariance for video images x and y as in Eq. (3.3)

\[
L_{xy} = \frac{(2\mu_x\mu_y + C_1)}{(\mu_x\mu_x + \mu_y\mu_y + C_1)}
\]

(3.3)

where \(C_1 = (K_1 \times 255)^2\). Similarly, the contrast effects are calculated as in Eq. (3.4)

\[
C_{xy} = \frac{(2s_xs_y + C_2)}{(s_xs_x + s ys_y + C_2)}
\]

(3.4)

where \(C_2 = (K_2 \times 255)^2\). Finally, the structure comparison becomes as in Eq. (3.5)

\[
S_{xy} = \frac{(r_{xy} + C_3)}{(s_x s_y + C_3)}
\]

(3.5)

where \(C_3 = C_2/2\). Here \(K_1\) and \(K_2\) are chosen to be \(K_1=0.3\) and \(K_2=0.9\). When the exponents are set to the default value \(\alpha = \beta = \gamma = 1\), and \(C_3 = C_2/2\), then the SSIM index formula simplifies to Eq. (3.6).

\[
SSIM(xy) = \frac{(2\mu_x\mu_y + C_1).(2\sigma_{xy} + C_2)}{(\mu_x^2 + \mu_y^2 + C_1).(\sigma_x^2 + \sigma_y^2 + C_2)}
\]

(3.6)

Based on this, offline algorithms were used to compare the similarity of the transmitted and its corresponding received video. In Fig. 3.20, SSIM is about 88%-96% for all modulations over the clear, coastal and harbor I. At harbor II, the corresponding SSIM of all modulations drop down except for 8-QAM which remains at around 95%. As stated earlier, as more bits per symbol are represented in higher order modulations, we increase the spectral efficiency. However, in this noisy channel, the probability of error increases for the correct placement of points on the constellation graph in 8-PSK and although its corresponding SSIM is about 70%, it still has the lowest similarity index resulting in the most distorted video image of all used modulation.
schemes.

Figure 3.20: SSIM results for video images.

3.5 Discussions

In this work, we experimentally demonstrated a reconfigurable and cost-effective communications system for underwater live video streaming using wireless optical communications link. We evaluated our system using a testbed experiment over 5 m distance using four modulation techniques in four ocean water types. The video streaming system utilizes USRP-RIO hardware and LabVIEW software packages. This is integrated into the wireless optical transmission link which uses a commercially available TO-9 packaged pigtailed 520 nm LD as the transmitter and an APD module as the receiver. The live video transmission has been demonstrated and proven
to be reliable resulting in open eye diagrams, clear constellation points and BER of $1.0 \times 10^{-9}$ for clear, coastal, harbor I, and harbor II for all modulations, and $9.9 \times 10^{-9}$ for 8-PSK. The quality of the received video was additionally evaluated using SSIM metric which resulted in values up to 96% similarity for all water types and about 70% for harbor II, indicating a very high similarity between the sent and received videos. Our comprehensive study on real-time video transmission over different ocean water types and various modulation techniques paves the way for designing better UWOC systems for next-generation underwater video applications.

Although these results outperformed any previous work, and were received greatly by the research community and interested parties in the underwater exploration, we still strive to make enhancements to the system’s performances in pursuit for a challenge. We had the aim to provide fundamental concepts through novel designs that would revolutionize the underwater exploration in this modern age. As the technology is envisioned for use in underwater vehicles, our target, in addition to that, is to lay the foundations for ultra-high definition video transfer underwater. Through the use of higher orders of modulations combined with multi-carrier schemes in a cross-layer implementation, and by implementing rather a new setup configuration that enables feedback generation by establishing bidirectional links for an adaptive and optimized video transmission system. We provide in the next chapter, a thorough investigation of the concepts and system’s design, the experimental setup and system’s specifications, the cross-layer approach and implementation. We also provide an exhaustive analysis of the results and discuss the throughput performance and received video quality under various modulations and ocean water types.
Chapter 4

UHD video transmission over bi-directional underwater wireless optical networks

In this work [10], we propose using Bi-DIR communication links for the purposes of underwater UHD and live video streaming on the downlink channels while providing the feedback control messages on the uplink channels. The additional uplink channel provides necessary feedback about the channel conditions, the possibility of using this to transmit and receive control messages, and real-time commands for maneuvering the ROVs. Furthermore, when a wireless optical feedback link is established, movements of multiple robots can be coordinated where the ROVs can move freely and send signaling data and receive further maneuvering instructions in real-time. The feedback received as well on the underwater channel conditions enables the instantaneous throughput adaptations to the noise levels and transmission power, and thus helps in reducing the energy loss while improving the modulation and coding schemes.

Overall, we experimentally demonstrate the feasibility of the proposed system and evaluate its performance under higher orders of QAM implemented with OFDM modulations. We examine our system by deployments in various underwater channel conditions and analyze the throughput and quality of the received UHD live video streams. The results reveal that UHD video streaming is possible not only in the traditional uni-directional communication setup but also where feedback control messages are established through Bi-DIR links.
4.1 System model

In our model, we integrate LabVIEW software packages into USRP-RIO hardware to transmit live streams of UHD video underwater. We use two USRP-RIO devices operating as Client/Server model. The system’s block diagram is shown in Fig. 4.1.

Figure 4.1: Block diagram of the system.

4.1.1 Downlink transmitter module

In the Down-Link (DL) the video data are first read from a User Datagram Protocol (UDP) socket into the (Server) when provided by an external application using the (UDP read) command. The video payload is fed into the Transport Block (TB) in
the Field Programmable Gate Array (FPGA) where Medium Access Control (MAC) layer (MAC TX) implementation will add a header with the number of video payload bytes to the TB, followed by the video bytes and ending with padding. The TB data will be encoded and modulated as a DL signal and will be sent by the DL transmitter denoted as (PHY downlink TX).

This physical layer of the DL transmitter will also encode the Physical Downlink Control Channel (PDCCH) and the Physical Downlink Data Shared Channel (PDSCH). Also, create the DL video signal as a digital baseband I/Q data, do the resource mapping, and the OFDM modulation. The video signal is then transmitted through the optical link using the green LD into the underwater channel.

4.1.2 Downlink receiver module

When the video signal is received at the second USRP-RIO (Client) at the physical layer of the DL receiver denoted as (PHY downlink RX), it gets demodulated and decoded at the physical channels. This involves also processing of the Primary Synchronization Sequence (PSS) based synchronization, the demodulation of the OFDM, the resources de-mapping, the channel estimation and equalization, the decoding of the control channel PDCCH, and the decoding of the downlink data shared channel PDSCH. It will then be followed by disassembling of the transport block TB and extracting the payload bytes at the MAC RX. Finally, this payload data is written to a UDP socket using the (UDP write) command. The video data can then be displayed by the external application and processed by the host PC.

4.1.3 Uplink transmitter module

In the Up-Link (UL) in order to provide the feedback on the channel and reception status to the first USRP-RIO (Server), the channel estimation that was done on the PHY downlink RX at the FPGA (Client) will be fed into the Host (Client) application
to calculate the **Signal-to-Interference-Noise-Ratio (SINR)**. The **SINR** is based on the channel estimation used for **PDSCH** decoding and using **Cell-specific Reference Signals (CRS)**. The feedback generation process creates a message for the measured **SINR** and the **ACK/No Acknowledgment (NACK)** information which is the **Cyclic Redundancy Check (CRC)** results of the **PDSCH** decoding of the previously received video frame.

The physical layer of the **UL** transmitter denoted as (PHY uplink TX) will perform a similar role as that of the (Server), but in the **UL** direction. It will encode the physical channels and create the **UL** signal as digital baseband I/Q data. It will also encode the **Uplink Data Shared Channel (PUSCH)**, perform the resource mapping, and do the **OFDM** modulation. The feedback signal is then transmitted through the optical link using the blue **LD** into the underwater channel.

### 4.1.4 Uplink receiver module

When the feedback signal is received at the first **USRP-RIO** (Server) at the physical layer of the **UL** receiver denoted as (PHY uplink RX), it gets demodulated and decoded at the physical channels. This includes **OFDM** demodulation, resource demapping, channel estimation and equalization, and decoding of the physical uplink data shared channel **PUSCH**. At the feedback analysis stage the **SINR** and the **ACK/NACK** information will be fetched from the feedback message.

The subsequent process is to perform the throughput rate adaptation by adjusting the **Modulation and Coding Scheme (MCS)** based on the measured and reported **SINR** in order to minimize the **Block Error Rate (BLER)** of the **PDSCH** decoding. This will close the feedback loop and pass the new and improved settings to the PHY downlink TX at the start of the new session of underwater **UHD** video transmission.
4.2 Experimental setup

4.2.1 Downlink optics setup

The actual photograph of the Bi-DIR underwater UHD video transmission system setup is shown in Fig. 4.2. We utilize a 15 mW commercially available, TO-9 packaged and single-mode fiber-pigtailed green LD (Thorlabs LP520-SF15) as the optical transmitter for the DL video streaming channel.

![Actual photograph of the water tank showing: Downlink Channel (a) Green laser and driver mount, (b) collimator lens, (c) mirror, (d) green laser beams underwater, (e) mirror, (f) focusing lens, (g) avalanche photodiode (APD), and Uplink Channel (h) Blue laser and collimator lens, (i) mirror, (j) blue laser beams underwater, (k) mirror, (l) focusing lens, (m) avalanche photodiode (APD).]

Fig. 4.3(a) presents the light-current-voltage (L-I-V) curves of the pigtailed green LD having a threshold current of 28 mA, and a slope efficiency of around 3.1%. Also in (b) the graph shows the emission spectra of the green LD under different injection currents obtained using a high-resolution spectrometer (Ocean Optics HR4000). The FWHM of the green LD is 1.0 nm. The emission center wavelength at 70 mA is around 517.6 nm and slightly changes with increasing injection current.

The DL generated video packets, that were transmitted from the first USRP
Figure 4.3: Characteristics of the 520 nm LD at 25°C: (a) L-I-V curves (b) optical spectra with increasing bias currents.

(Server) transmitter, were superimposed on the green DC laser bias current using the built-in Bias-Tee RF input within the green laser driver mount (Thorlabs LDM9LP). The output radiation of the green LD was collimated by a plano-convex lens (Thorlabs LA1027-A) of 25.4 mm diameter and 35 mm focal length to produce a parallel beam which is incident on the underwater channel in the DL direction. The underwater channel was simulated using a water tank made of PVC with 1.5 x 2.7 x 0.63 m³ dimensions. The tank was filled with municipality fresh tap water with an estimated attenuation coefficient = 0.071 m⁻¹ [56], which is similar to the clear blue ocean water type. The optical path length for the DL in the water tank was extended up to 4.5 m using mirrors installed at both ends of the tank. After propagating through the water tank, the optical beam was focused into a high sensitivity silicon avalanche photodiode (Menlo Systems APD210) receiver unit using a 25.4 mm focal length lens (Thorlabs LA1951-A). The APD has 1 GHz cut-off bandwidth, 0.5 mm active diameter, 0.4 pW/Hz¹⁄² noise equivalent power NEP and around 13 A/W responsivity at 520 nm. The video packets are finally received by the second USRP receiver (Client) for post processing by the host PC.
4.2.2 Uplink optics setup

The UL channel utilizes another 15 mW commercially available, TO-9 packaged and single-mode fiber-pigtailed blue LD (Thorlabs LP450-SF15) as the optical transmitter for the feedback control channel. Fig. 4.4(a) presents the light-current–voltage (L-I-V) curves of the pigtailed blue LD having a threshold current of 32 mA, and a slope efficiency of around 4.8%. Also in (b) the graph shows the emission spectra of the blue LD under different injection currents obtained using a high-resolution spectrometer (Ocean Optics HR4000). The FWHM of the blue LD is 0.9 nm. The emission center wavelength at 70 mA is around 447.3 nm and slightly changes with increasing injection current.

![Figure 4.4: Characteristics of the 450 nm LD at 25°C: (a) L-I-V curves (b) optical spectra with increasing bias currents.](image)

Similarly, the UL generated feedback control packets, that were transmitted from the second USRP (Client) transmitter, were superimposed on the blue DC laser bias current using the built-in Bias-Tee RF input within the blue laser driver mount (Thorlabs LDM9LP). The output radiation of the blue LD was collimated by a plano-convex lens (Thorlabs LA1951-A) of 25.4 mm diameter and 25.4 mm focal length to produce a parallel beam which is incident on the underwater channel in the UL direction. The optical path length for the UL in the water tank was extended up to 4.5 m using mir-
rors installed at both ends of the tank. After propagating through the water tank, the optical beam was focused into a high sensitivity silicon avalanche photodiode (Menlo Systems APD210) receiver unit using a 25.4 mm focal length lens (Thorlabs LB1761). The APD has 1 GHz cut-off bandwidth, 0.5 mm active diameter, 0.4 pW/Hz$^{1/2}$ noise equivalent power NEP and around 5 A/W responsivity at 450 nm. The feedback control packets are finally received by the first USRP receiver (Server) for evaluation, rate adaptation and adjustment of the transmission parameters.

Fig. 4.5 shows the schematics of the system. All measurements were taken under normal room illumination conditions. The water turbidity level is changed by adding accurate Maalox solution based on [95], in order to simulate various turbidity levels in the underwater channels as in Table 4.1. The amounts of Maalox concentration added to achieve the desired absorption and scattering coefficients corresponding to the clear and harbor II water types, respectively, are shown in the last column of Table 4.1 and is based on [96]. After the addition of each Maalox concentration, we sufficiently stirred the mixture to obtain a uniform water channel before proceeding with the measurements.

<table>
<thead>
<tr>
<th>Water Type</th>
<th>a (m$^{-1}$)</th>
<th>b (m$^{-1}$)</th>
<th>c (m$^{-1}$)</th>
<th>V(µL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear water</td>
<td>0.114</td>
<td>0.037</td>
<td>0.151</td>
<td>77.1</td>
</tr>
<tr>
<td>Harbor II water</td>
<td>0.366</td>
<td>1.824</td>
<td>2.19</td>
<td>1118.7</td>
</tr>
</tbody>
</table>

4.3 OFDM Implementation

4.3.1 Modulation techniques

The debate of whether to use conventional binary modulations, such as on-off keying OOK which seems to be simpler, but suffers somewhat from multipath dispersion
at high bit rates. In the highly noisy and dispersive underwater channel, if we take K data bits to form QAM data symbols, and then map those data symbols onto S OFDM subcarriers, then we generate in the electrical domain a multiplication of K and S data bits. Such configuration reduces the cost of using high-speed optical devices, while we are utilizing the advanced Digital Signal Processing (DSP) features provided by the USRP circuits which makes the implementation much easier and cost effective.

Also, in the multicarrier modulations the symbol period is large enough so that any delay from the channel is negligible. This is essential factor in real time video applications. Our approach main objective is to utilize to the most the spectral efficiency of the communication system, while still allowing very high data rate transmissions. The integration of a video decoder into the system is of a great challenge, and adding another dimension of complexities into the system that is not favorable
when conventional modulation scheme is used. There are many other benefits of using multicarrier modulations over basic modulations. To give few examples, such as ease of signal processing where OFDM systems enable the use of pilot subcarriers to be made at the transmitter side. This facilitate an easier way of estimating the channel and phase. Another benefit is in the use of higher order modulations beyond 2 bits per symbol while keeping the complexity at low level by utilizing the software packages to reconfigure the DSP and DAC. A more complicated optical modulator configuration would be required if higher orders of OOK is implemented.

Moreover, the narrow spectral shape of the OFDM signal is bounded, making the filtering effects negligible, when compared to pulse shaping and timing jitter in single carriers. As the OFDM signal is generated in the frequency domain, its scalability to bandwidth is maintained thanks to the orthogonality features. More important benefit is in the use of IFFT/FFT modules to reduce the computational complexity. Data Rate adaptation to the channel conditions is also achieved when using OFDM by the bit and power loading being adjusted at the transmitter side. Also the sampling rate in OFDM schemes is not necessarily twice the band rate, which facilitate the use of the available ADC and DAC circuits (MS/s range), while we notice the use of Gs/s encoders for the OOK optical systems. The cost of such waveform generators and oscilloscopes is almost 10 times higher, and yet are not able to generate or process video streams necessary for our experiment.

4.3.2 OFDM details

The physical channels and signals implemented in our framework used OFDM modulation to maximize the bandwidth utilization (bits/s/Hz), and are in general complying with the specifications in [100–102]. Prior to the generation of the OFDM signals, initially the input data bit sequence is converted from serial into parallel (S/P), encoded and mapped into QAM symbols. This output sequence of complex waveforms
from the constellation mapping form a vector input to the 2,048-point Inverse Fast Fourier Transform (IFFT) to form the OFDM signals, making 2,048 subcarriers per symbol in the frequency-domain. After that, a conversion from parallel to serial (P/S) is performed before the insertion of the Cyclic Prefix (CP), which is enabled in normal mode with length of 166 for symbol 0, and 144 for symbols from 1 to 6. The CP helps to suppress the link ISI. Following a digital-to-analog conversion (DAC), the QAM-OFDM signals are superimposed on the built-in Bias-tee within the laser diode mount to directly modulate the LD. After the signal is transmitted through the underwater channel, at the receiver side the inverse processes are performed; ADC, the removal of CP, S/P, the FFT to convert to frequency-domain subcarriers and for demapping back to QAM symbols, and finally P/S conversion. The OFDM parameters configuration comprise of 15khz of subcarrier spacing when normal cyclic prefix setup is used. Each transmission frame is 10 ms long and is made up of 10 subframes with length of 1 ms. This comprises 30,720 complex time domain baseband samples at a rate of 30.72 MS/s. Each subframe is divided into 14 symbols, with symbol duration of (2048 multiples of the sampling period). Out of the 2,048 subcarriers there are 1,200 subcarriers used for the transmission and organized in sets of 12 subcarriers to form 100 physical resource blocks (PRBs) and there are 7 OFDM symbols per RBE.

4.4 Experimental results and discussions

In this section, we present our experimental results as follows: visual analysis, throughput analysis and PSNR analysis.

4.4.1 Visual analysis

We start our analysis with the visual influences and aspects of the performance. Fig. 4.6 shows the constellation graphs for harbor II water when the UHD video, with
4K resolution of 4096 x 1762, and audio track are transmitted over the DL channel when using 64-QAM, 16-QAM, and QPSK modulation schemes, as in (a), (b), and (c) respectively. The figure in (d) shows the QPSK modulation scheme for the UL feedback channel. We observe that the constellation maps are fairly distinguishable.

Figure 4.6: Constellation graph harbor II water: (a) 64-QAM, (b) 16-QAM, (c) QPSK, (d) feedback QPSK.

In Fig. 4.7 we provide snap shots that shows very clear details and bright colors of the (a) transmitted and (b) received UHD video when using 64-QAM modulation scheme and in harbor II water type. Those video samples are from (Sintel), the Durian Open Movie project by Blender Foundation [103]. Fig. 4.8 shows another video snapshot from same project that present clear details and ultra-high resolution of the received video streams.

Figure 4.7: Video snapshot, harbor II water, 64-QAM, 4K resolution: (a) transmitted video, (b) received video underwater.
4.4.2 Throughput analysis

In the following, we present the UHD video transmission throughput analysis. In Fig. 4.9, we show the measured average throughput against video resolutions when different streams are transmitted in different water types and using different modulation schemes. We use the following verified resolutions: 4096 (4K UHD), 1080 (HD), 720, and 480 for the same video.

It is apparent that the average throughput decreases when lowering down the video quality. In addition, it is interesting to note that our experiment verified that the throughput was not only decreasing while the water turbidity increases when going from clear water type to harbor II ocean water, but also that the modulation scheme effects the video transmission throughput when the 4K UHD video is sent more than the other lower resolutions. From the graph, we zoomed into the 4K UHD video throughput area and found that the average throughput is the lowest when using QPSK in harbor II ocean water. The second lowest is when using QPSK in clear water. While comparing 64-QAM and 16-QAM, an interesting finding is that the later outperformed the 64-QAM modulation in harbor II ocean water, and the 16-QAM performance was not heavily affected by the water turbidity.

When transmitting UHD video in clear water type, the 16-QAM and 64-QAM modulations are relatively in close proximity. This is suggesting there are tradeoffs
between the spectral efficiency provided by the 64-QAM scheme and its throughput performance, and the tradeoff becomes apparent in all aspects of performance as we increase the video quality (resolution) as we just noticed and will again realize in the following set of figures. Using OFDM with higher orders of modulations such as 64-QAM, although it facilitates increasing the bandwidth per symbol, it makes the selectivity of individual subcarrier frequencies much harder in such a noisy channel.

We show in Fig. 4.10, the throughput variations over time for video streams with the resolutions of 1080 and 480 in clear and harbor II ocean water types, while the modulation scheme is set to 64-QAM. Interestingly enough that the patterns of the throughput trace are matching, however the comparison suggests that the effects are more for the higher resolution. This is in agreement with our previous findings in Fig. 4.9.

We now examine, in more details, the throughput of the 4K UHD video streams
Figure 4.10: Throughput over time for the 1080 and 480 video resolutions.
when transmitted in harbor II ocean water type. Fig. 4.11 shows the throughput over the whole video time (about 15 minutes), under different modulation schemes. In (a) 16-QAM and 64-QAM in (b). These two figures show the similarity of both throughput spectrums. However, we clearly notice the QPSK in (c) is clipped at the maximum rate it can support (around 15 Mbps), while this agrees with the throughput shape in clear water when QPSK is used as in (d).

Figure 4.11: Throughput over time for the 4K UHD video resolution in harbor II water using: (a) 16-QAM, (b) 64-QAM, (c) QPSK, and in (d) clear water using QPSK.
In Fig. 4.12 we examine more closely the throughput of the 4K UHD video transmission in harbor II water type to help us compare the performance of the different modulation schemes. Part (a) shows the three schemes QPSK, 16-QAM, and 64-QAM altogether and overlapping except where QPSK is clipped as we explained in Fig. 4.11. It can be also noticed that 16-QAM is the highest throughput. In order to clearly show this, we zoomed into a portion of the throughput graph in part (b) of the figure.

![Graph showing throughput over time for 4K video resolutions in harbor II water for QPSK, 16-QAM, and 64-QAM.

Figure 4.12: Throughput over time for the 4K video resolutions in harbor II water for QPSK, 16-QAM, and 64-QAM: (a) 15 minutes (b) zooming into 3 minutes only.
Finally, we show in Fig. 4.13 the comparison of the performance of the 64-QAM modulation scheme for the 4K UHD video streams when sent into the clear water against the harbor II. Part (a) shows the throughput for the whole time of the video and (b) for only 3 minutes to easily recognize the difference. It shows that the throughput is lower in harbor II ocean water. However, it is important to mention that the throughput traces are very closely matching which proofs that the performance of the system is stable even under the most turbid ocean water condition, and matches that of the clear water type while considering that the video streams is UHD.

Figure 4.13: Throughput over time for the 4K video resolutions using 64-QAM in clear water and harbor II water: (a) 15 minutes (b) zooming into 3 minutes only.
The throughput analysis in our work refers to the instantaneous video bit rate that is transmitted and received in real time and with UHD quality, which normally require 30 Mbps at the highest video resolution. The USRP digitizer system with 120 MHz sample clock is capable of providing up to 75 Mbps and worst case latency of about 0.8 ms for the maximum 100 PRBs (physical resource blocks) corresponding to the 1,200 OFDM transmission subcarriers, and when the highest modulation and coding scheme of order MCS28 (referring to 64-QAM-OFDM) is implemented. This would be more than sufficient to meet our objective and successfully transmit UHD video into the underwater wireless optical communications setup.

4.4.3 Video quality PSNR analysis

In the last part of this analysis, we discuss the effects of using different modulation schemes on UHD video transmission quality in the most turbid harbor II water. We use PSNR in our analysis to show the difference between the transmitted and received video streams. As we show in Fig. 4.14, we consider the resolution of the video streams to be 480, 720 and 1080. It is apparent that 1080 is the highest average PSNR among all the resolutions, at the top of the figure, and there is no difference between transmitting in the tap water and clear water.

While also noticing that the average PSNR will drop down when we transmit the video in harbor II ocean water type. There is no apparent difference between the three modulations schemes QPSK, 16-QAM and 64-QAM when transmitting in tap and clear water. However, an interesting finding is that the 64-QAM produces the least average PSNR when transmitting those resolutions.

The results presented in Fig. 4.15 show the effects of using different modulation techniques on transmitting 4K UHD video in different water turbidity channels. Tap and clear water types do not present a remarkable difference between the modulations, while in harbor II it presents clear evidence that the QPSK will provide the least
average PSNR. On the other hand, in harbor II, the results do not show big difference between using either 16-QAM or 64-QAM on the video quality.

### 4.5 Discussions

In this work, we experimentally demonstrated an UHD quality and real-time video streaming into an UWOC link up to 4.5 m distance using QPSK, 16-QAM and 64-QAM OFDM modulation schemes in clear and harbor II ocean water types. The communication system is based on Bi-DIR framework that can transmit the video using DL channel and receive the feedback control on the UL channel. The UHD video system utilizes LabVIEW software packages built into USRP hardware. The video packets are transmitted on the DL channel which is integrated into the wireless optical transmission link using a commercially available TO-9 packaged pigtailed 520 nm green LD as the transmitter and an APD module as the receiver. The feedback control packets are transmitted on the UL channel which is integrated into the wireless link.
optical transmission link using a commercially available TO-9 packaged pigtailed 450 nm blue LD as the transmitter and an APD module as the receiver. The UHD and live video transmission has been demonstrated and proven to be reliable resulting in clear constellation points and clear video images. The achieved throughput for streaming UHD video is 15 Mbps for QPSK and 30 Mbps for both 16-QAM and 64-QAM in harbor II water type. Additionally, the PSNR metric was used to evaluate the quality of the received UHD video. The results values were up to 16 dB for 64-QAM when streaming UHD video in harbor II ocean water and 22 dB in clear ocean water. When our proposed solution is integrated into underwater robotics and underwater wireless sensor networks, it will enable a new era of ocean discovery and exploration. Collecting research samples for onshore testing and ROV periodic surfacing is minimized. The underwater life can be inspected, monitored, and repaired as required while keeping it within its natural boundaries.

In this chapter, we laid the foundation for an ultra-high definition video transfer
in underwater environments. It is time to consider extending this work, to what we introduce in the next chapter. A multi-channel configuration is proposed in order to enhance the reliability of the system and increase the probability of receiving video packets that can be decoded. Due to the current limitations on implementing the conceptual design of multi-channels experimentally, we rather perform mathematical analysis and compare it to simulations. In the next chapter, we provide for the first time, comprehensive analytical discussions on the concept of multi-channel video transmission underwater. We introduce the system’s design and queue model. We derive the mathematical model for the end-to-end delay, and blocking probability. Also, an expression for the minimum number of channels is derived. At the end we provide our comparison results between the analytical model and the simulation that we performed. A complete analysis of the results is provided.
Chapter 5

Video delay analysis and blocking probability in multi-channel underwater wireless optical networks

In this work [1], we aim to provide analytical study that will enable researchers to make the best design of network topologies to meet the optimum QoS for the delay and packet loss when using UWON. Also, to provide researchers with performance means to design an optimal routing policy for contingency planning and to overcome the NLOS situations. Moreover, we hope to help engineers design multi-channel systems with optimal capacity assignment to each underwater wireless optical channel. In order to make this possible, we examine the performance of video transmission over an UWON system that is employing multi-channel diversity gain from a single sender through multiple channels underwater to a single receiver. We examine this network using an $M/G/1$ queuing theory model to quantify the system’s performance. We develop an approximate expression for the probability of blocking at the receiver side considering an acceptable QoS for a given minimum E2E delay. Given those constraints, we develop an expression for the minimum number of channels that can provide us with that acceptable QoS value. Finally, we perform simulation measurements to validate our model.

That should provide some basis for exploring the effects of using multiple underwater channels on improving the received video quality and on the overall performance and resilience of the UWON system under various channel conditions. We assume that all of the channels are located with an equal separation distance in a line perpendicular to the transmission direction. We also assume that the multi-channel
transmission is based on an equal power allocation for transmitters, i.e., $P_i = P/M$. Here, we assume that the fading of each link is independent from the others. We expect to show that increasing the number of independent links provides significant performance improvement. Hence, in our approach we care to find the minimum number of those channel links that satisfy the acceptable delay constraint.

5.1 Proposed System Model

In our system, we consider an underwater wireless optical network, such as Fig. 5.1, in which a sender transmits video using an equally spaced laser diode (LD) sources through $M$ underwater optical channels to an equivalent number of avalanche photodiode (APD) detectors. We assume that all of the channels are located in line-of-sight (LOS) to the receiver and with an equal separation distance. We also assume that the multi-channel transmission is based on an equal power allocation for transmitters, i.e., $P_i = P/M$. Here, we assume that the fading of each link is independent from the others, in order to make an independent and identically distributed (i.i.d) channels model. The queue model for the multi-channel setup of the underwater wireless optical network is shown in a simplified form as in Fig. 5.2, where the arrivals to the

![Figure 5.1: An overview of the multi-channel underwater wireless optical system.](image-url)
network are made into multiple copies and sent through the available channels to the receiver.

The incoming video packets are modeled with an exponential inter-arrival times having rates $\gamma_i(v)$, where $i = 1, 2, ... M$, and $M$ is the maximum number of available channels. When the video signal arrives from external sources, it is wrapped into packets that include guard bits, synchronization bits, and pad bits which we will call from now on as control packets. These control packets are exchanged with the receiver from the sender’s internal sources to manage video packets transmission and to provide statistics about errors and packets loss. The channels are modeled as independent single server facilities with two class queues where video packets are transmitted to the receiver node.

Each path that these packets traverse from the sender to the receiver is characterized in our model by an ordered set of channels $\pi_k$, and each channel has a capacity $C_i$. The service time at each channel is assumed to be exponential with parameter $\lambda = \lambda_v + \lambda_c$.
μC_i. We assume that the arrival of class k packets to the network is to be Poisson distributed with rates \( \lambda_v \) for the video packets, and \( \lambda_c \) for the control packets. The arrival to the network in general is:

\[
\lambda = \sum_{i=1}^{\infty} [\lambda_i(v) + \lambda_i(c)] = \sum_{i=1, k \in \{v,c\}} \gamma_i(k)
\]

(5.1)

Hence, we consider an infinitely continuous transmission for the live streams of video packets. Video packets are assumed to originate only from the source, while control packets can arrive from external sources. In general, there are two different flows into the network (i.e. video, and control) if control packets are meant for commanding an underwater robot, for instance, but in our case we assume the control packets are for managing the video transmission signal and is wrapped together with the video payload into one single transmission packet. Going forward we will drop the control packet notion and consider a flow all together to be a video packet. To formulate this concept (i.e., multiple copies of the same packet through the different \( M \) channels), the arrival rate to each channel is equally distributed with the same arrival rate:

\[
\lambda_i(k) = \sum_{i=1}^{M} \gamma_i(k) = \begin{cases} 
\gamma_k, & i \in \pi_k \\
0, & \text{otherwise}
\end{cases}
\]

(5.2)

where \( k \in \{v, c\} \) is the packet class index in the system, and \( \pi_k \) is the set of channels traversed by class \( k \) packets.

In our system, we are looking at each channel as a queue in isolation with an exponentially distributed service time that has a mean of \( X_i \), for each channel where \( i \in \{1, 2, ..., M\} \). Our objective in this framework is to identify a minimum QoS requirement that defines the latency experienced by the received video packets. We therefore set a minimum acceptable time delay from the moment each video packet
is transmitted till it is delivered correctly at the receiver, and we call this threshold as \( T_{QoS} \). Any video packet with an overall delay resulting from waiting due to other packets are already being in the queue or in service either at the channels or at the receiver, or due to an excessive propagation delays at the channels, resulting in the delays exceeding \( T_{QoS} \) upon arriving the receiver node will be dropped. This constrain is implemented before the receiver, but we also implement the quality check QoS constraint at the receiver queue. Thus, if we let \( D \) be a random variable that stands for a video packet time delay, then the probability of dropping a video packet at the receiver node is:

\[
P_{\text{blocking}(v)} = \Pr \left\{ D(v) > T_{QoS(v)} \right\}
\]

We also realize our system to be based on a multi-channel configuration, and in order to improve the reliability of the system and fully utilize the diversity of all available channels, we assume the use of simple repetition coding that generates multiple copies of the same packet to be transmitted through each path with the same probability \( p_m \). At the receiver, a maximum of \( M \) packets will arrive and we are considering one technique that is often used in such systems. We assume that the arriving video packets are queued based on the precedence of their arriving time, and then wait for a quality check to be performed based on a preset QoS metric. The waiting time at the receiver buffer is based on the probability that a video packet is successfully decoded using packet \( i \) of the \( M \) transmitted packets, and is denoted by \( P_{S_i} \). It is equal to the conditional probability that we use \( i \) versions of the packet to successfully decode the video, given that at least one packet is decoded in order to satisfy the queue stability condition.

\[
P_{S_i} = \frac{(1 - p)^{i-1} \cdot p}{\sum_{m=1}^{M} (1 - p)^{m-1} \cdot p} = \frac{(1 - p)^{i-1} \cdot p}{1 - (1 - p)^M}
\]
5.2 Analysis

In this section, we present our analytical expressions for the video transmission time Delay $D$ experienced by any $K$ classes of packets, in addition to finding the video packet dropping probability. Our derivations are based on the standard methods for $M/G/1$ queues as in [104]. We start with providing a summary of notations as in Table 5.1.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>Number of multi-channels in the system</td>
</tr>
<tr>
<td>$K$</td>
<td>Packet classes</td>
</tr>
<tr>
<td>$i$</td>
<td>Channel index</td>
</tr>
<tr>
<td>$\lambda_{(v),i}$</td>
<td>Poisson arrival rate of video packet to Channel $i$</td>
</tr>
<tr>
<td>$\lambda_{(c),i}$</td>
<td>Poisson arrival rate of control packet to Channel $i$</td>
</tr>
<tr>
<td>$\lambda_{k,i}$</td>
<td>Aggregate Poisson arrival rate of classes $k$ going to Channel $i$, $k \in {v,c}$</td>
</tr>
<tr>
<td>$X_j$</td>
<td>Service time random variable for packet $j$</td>
</tr>
<tr>
<td>$\chi_i$</td>
<td>Service time random variable for Channel $i$</td>
</tr>
<tr>
<td>$p_{k,i}$</td>
<td>Probability of scheduling a packet flow of class $k$, $k \in {v,c}$ into Channel $i$</td>
</tr>
<tr>
<td>$\rho_{k,i}$</td>
<td>Utilization of packet class $k$, $k \in {v,c}$ at Channel $i$</td>
</tr>
<tr>
<td>$R$</td>
<td>Residual service time</td>
</tr>
<tr>
<td>$W_{k,i}$</td>
<td>Waiting time in the queue for packet class $k$, $k \in {v,c}$ at Channel $i$</td>
</tr>
<tr>
<td>$\omega_{k,i}$</td>
<td>Waiting time at receiver for packet $i$ of class $k$, $k \in {v,c}$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Average response time at Channel $i$</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>Propagation delay at Channel $i$ from Green Laser Diode source to Avalanche Photo-Detector receiver</td>
</tr>
<tr>
<td>$N_{k,i}$</td>
<td>Number of packets scheduled in the queue with class $k$, and Channel $i$, $k \in {v,c}$</td>
</tr>
</tbody>
</table>

Because we are considering $M$ channels in our proposed model for the multi-channel configuration of the UWON, although we assumed video packets can have an exponentially distributed inter-arrival time, their service time however can be different and does not necessarily have an exponential distribution, it can be considered
arbitrary. Therefore, we will model each channel as a queue in isolation and an $M/G/1$ queue and the receiver as an $M/G/1$ queue as well. To simplify derivations, we assume that each packet has a separate queue in logical sense, and when each channel represents a single server, which when becomes free, packets from the head of the non-empty queue enters that channel with free server for transmission. Also, when packets exit the transmission channels and arrive at the receiver queue, they wait in sequence ordered by their arrival time to further undergo a quality check. At least one packet is successfully decoded in our assumption which satisfy the quality check and arrived before any other decodable packet. Packets that do not satisfy the quality check will be dropped. When a decodable packet is found the queue buffer will be flushed and the remaining packets will be dropped.

The probability of successfully finding a decodable packet is provided above in (5.4). There are no priority over any packet, the arrival rates $\lambda_1, \ldots, \lambda_i$ (Poissonian), and the expectation and second moment of the service time are $\bar{X}$ and $\bar{X}^2$. The stability condition of the queue: $\rho_1 + \cdots + \rho_i < 1$ is viable.

To start with, we are interested in obtaining the mean waiting time $\overline{W}$ and second moment $\overline{W^2}$ that will be experienced by video packets at each underwater optical channel. As we are looking into each channel as a queue in isolation we will remove the channel index $i$ to simplify the notations but we will use $i$ as a packet index in the receiver queue whenever required. The average waiting time in the system is based on the summation of waiting times in the channels $\overline{W_{ch}}$ as well as at the receiver $\overline{W_{rx}}$:

$$E[W] = E[\overline{W_{ch}}] + E[\overline{W_{rx}}] \quad (5.5)$$

To find the average waiting time at the channels, we will start in the same way as in the derivation of the Pollaczek – Khinchinin for our proposed type of queueing
system. The (P-K) formula states the following:

\[ E[W_{ch}] = \frac{E[R]}{1 - \rho} = \frac{\lambda \cdot E[X^2]}{2(1 - \rho)} \]  \hspace{1cm} (5.6)

Using the following notations: \( N_q^{(k)} \), which is the mean number of waiting class-\( k \) packets in the queue, \( W_q \), the mean waiting time of class-\( k \) packets, \( \rho_k \), the load of class-\( k \), or \( \rho_k = \lambda_k \cdot X_k \), and \( R \), the mean residual service time in the underwater optical channel (upon arrival), then video packets average waiting time in channels is:

\[ W_{ch} = R + X \cdot N_q \]  \hspace{1cm} (5.7)

The latter term represents the average time needed to serve the video packets ahead in the channel queue. By Little’s result we have \( N_q = \lambda \cdot W_{ch} \). Substituting in (5.7) above, we get: \( W_{ch} = R + \rho_v \cdot W_{ch} \). Rearranging the terms we get the waiting time for the video packets as:

\[ W_{ch} = \frac{R}{1 - \rho_v} \]  \hspace{1cm} (5.8)

In general, the total time spend in channels for class-\( k \) packets on the average can be found as:

\[ T_k = W_k + X_k + \tau_k \]  \hspace{1cm} (5.9)

where \( \tau \) is the propagation delay of the optical signal in the underwater channel, which we will elaborate with more details in the evaluation section later on in this paper. The mean residual service time \( R \) appearing in \( W_k \) can be derived by the same kind of graphical triangle trick as in the case of the (P-K) mean value formula as:

\[ R = \frac{1}{2} \sum_{n=1}^{N} \lambda_n \cdot X_n^2 \]  \hspace{1cm} (5.10)
The first moment of this residual time can then be written as

$$\bar{R} = \frac{1}{2} \left[ (\rho_v + \rho_c) \cdot \frac{\bar{X}^2}{X_v} \right]$$  \hspace{1cm} (5.11)$$

where $\rho_v = \lambda_v \cdot \bar{X}$ is the fraction of time the channel is serving the video packets. Making additional algebraic manipulations after raising both sides of (5.7) to the $2^{nd}$ power and taking expectation, we get the second moment of waiting time:

$$W^2 = \bar{N} \cdot \text{Var}(X) + \left[ \left( 1 + \frac{\rho_v}{1 - \rho_v} \right) \bar{R} \right]^2 + \text{Var}(R)$$  \hspace{1cm} (5.12)$$

where $\text{Var}(R) = \bar{R}^2 - \bar{R}^2$. Finally, we need to evaluate $\bar{R}^2$ by using the law of total expectation, $E[Y] = E[E[Y|X]]$:

$$\bar{R}^2 = \rho_v \bar{R}_v^2 + \rho_c \bar{R}_c^2 = \frac{1}{3} \left( \lambda_v + \lambda_c \bar{X} \right)$$  \hspace{1cm} (5.13)$$

At the receiver, the average waiting time is based on the probability of success defined in (5.4), and is given by:

$$E[W_{rx}] = \sum_{i=1}^{M} \omega_i \cdot P_{S_i} = \sum_{i=1}^{M} \omega_i \cdot \frac{(1 - p)^{(i-1)} \cdot p}{1 - (1 - p)^{M}}$$  \hspace{1cm} (5.14)$$

where $\omega_i$ is the service time taken by one packet $i$ in the receiver server and is assumed to be exponential with parameter $\mu_{rx}$.

The above equations complete the derivations of the waiting times and blocking probabilities for the video packet traffic both in channels and in receiver queues. We are now ready to proceed next to the derivations of the associated delays and minimum channels count.
5.2.1 Video Transmission Time Delay

The average time a class-$k$ packet spends in the system is:

$$T_k = [W_k + X_k + \tau_k]_{(ch)} + [W_k]_{(rx)}$$

Using Little’s formula, and the arrival rate of packets in the system for each class, while considering all packets, the average time delay per packet becomes:

$$T = \frac{\lambda_1 \cdot T_1 + \ldots + \lambda_K \cdot T_K}{\lambda_1 + \ldots + \lambda_K} + [W_k]_{(rx)}$$

In our case there are only two classes, video and control. Therefore, the mean time delay per packet simplifies to:

$$T = \frac{\lambda_v \cdot T_v + \lambda_c \cdot T_c}{\lambda_v + \lambda_c} + \sum_{i=1}^{M} \omega_i \cdot \frac{(1-p)^{(i-1)} \cdot p}{1 - (1-p)^M}$$

5.2.2 Minimum Channel-Count

In the last part of our analysis, we will try to find the minimum number of channels that can satisfy the delay QoS value that we set for our underwater wireless optical network, in such a way that we only use just enough channels that will improve the network reliability but not introduce excessive delays that can adversely affect the performance. The backscattering from an adjacent channel when increasing the number of channels in a confined space would increase the ISI in effect which we want to avoid.
The minimum channel-count is given by:

\[ M^* = \arg \min_s \{1^T s\}, \]

s.t.

\[ c1 : t \cdot s \leq t_{QoS}, \]  
\[ c2 : \sum_{i=1}^{M} S_i \geq 1, \]  
\[ c3 : s \in \{0,1\} \]  

where

\[ \overline{T}_i = (p_{k,i}) \cdot \overline{W}_{v,i} + (p_{k,i}) \cdot \overline{W}_{c,i} + \tau_i + \overline{w}_i \cdot P_{S_i}, \]

The vector \( s \) contains a series of 0 and 1 values that indicate whether a channel has satisfied the QoS constraint or not. The vector \( t \) contains the values of \( T_i \) for all channels, and the vector \( t_{QoS} \) contains the preset \( T_{QoS} \) values. Notice that in this optimization we try to find the minimum number of channels \( M \) by first building the vector \( s \) that when multiplied as a dot product multiplication by the vector \( t \) and cross comparing it element by element to the vector \( t_{QoS} \) we will be able to remove channels that did not satisfy the preset QoS values. When we insert the \( s \) into the minimization argument it will be multiplied by the vector 1. This process will sum these products as an increment by 1 each time we find a channel to eventually produce the count \( M \) of the minimum channels that satisfied the QoS. Hence, this optimization is an NP-complete problem and can be solved by the readily available ILP solvers, such as MATLAB-CVX software package.

### 5.3 Numerical Results

In this Section, we examine the validity of our model through simulation of different scenarios. We simulate a single \( M/G/1 \) queue with generally distributed service
times in order to verify the expressions we found earlier for $\bar{W}$ and $\bar{W}^2$. Although the service times are assumed to be exponentially distributed, we test the model for arbitrary service time distributions, because the formulas hold for single queue when the video arrivals are assumed to be Poisson distributed. The simulation model is written on MATLAB where a multi-channel configuration is designed. We considered a maximum of 4 channels as this setup is found optimum and fits within the space limits of a practical underwater wireless optical communications channel such as our exiting setup. The number of video packets and their average arrival-rate in our evaluation are $N = 45 \times 10^5$ and $\lambda = 1$; respectively. We based our settings on our findings in [10] that an ultra-high definition (UHD) video for UWON can be achieved with transfer rates of 30 Mbps. A maximum latency of 100 ms, and jitter of 30 ms can be tolerated for real-time and UHD video transmission in UWON. The propagation delay at the channels is based on the water refractive index at $20^\circ C$ which is $\approx 1.33$, so the speed of light in water is $2.25 \times 10^8 m/s$. We have also considered as a quality metric what we found in [9] that a Structural Similarity Index (SSIM), when it has a value of 70% it would provide us with an acceptable video quality that can be decoded. Therefore, we consider in our evaluation several scenarios where we set the QoS metric to 70%, 80% and 90%, in order to investigate what implications could this quality constraint have on the system’s performance.

Fig. 5.3 presents the blocking probability for a system of 4 channels, when the different values of quality metrics constraints are implemented. We observe that the more stringent our quality check is (i.e. at 90%), then the lower the success rate of delivering a decodable video packet with only one channel. However, by increasing the number of channels up to 4 channels, we observe that the failure rate is greatly minimized to negligible levels, and this supports our hypothesis.

Next, in Fig. 5.4, we show the strong agreement between the analytical and simulation results for the response time when 1, 2, 3, and 4 channels are available as
Figure 5.3: Blocking probability vs. preset QoS constraint for 4 channels.
Figure 5.4: Response time (simulation and analytical) vs. preset QoS constraint for (a) 1 channel, (b) 2, (c) 3, and (d) 4 channels.
in (a), (b), (c) and (d) respectively, and under the various QoS constraints that we implemented.

![Figure 5.5: Response time for QoS=90% versus number of channels (simulation).](image)

In Fig. 5.5, we present the response time versus the number of available channels while the QoS metric is set to 90%. It is apparent that while increasing the number of channels can help reduce the probability of failure it can also decrease the delay by about 15% at full load. We implemented a feedback channel in our simulation to guarantee fairness and stability of the queue. Nevertheless, we notice that the delay is still within the acceptable bounds of real-time video without having latency or jitter. The results for the response time reveal the benefits of using more channels, as we are within the bounds of acceptable QoS metric for decoding a good video packet, we therefore do not notice a big effect of setting the quality metric, opposed to when
having only a single channel. In Fig. 5.6, we present the response time versus the number of available channels while the QoS metric is set to 70%. In Fig. 5.7, we present the response time versus the number of available channels while the QoS metric is set to 80%.

![Figure 5.6: Response time for QoS=70% versus number of channels (simulation).](image)

Finally, in Fig. 5.8, we show the close match of the density functions of the proposed model response time using different distributions. We test Exponential, Gaussian, and Erlang-2 distributions as service times for the channels and receiver. A summary of the analysis is that we could improve the reliability of the system by greatly increasing the success rate of decoding the video from multiple copies received through the proposed multi-channel configuration. Even when implementing the most stringent quality metric, we did not exceed or even come close to the limits of the allowable
Figure 5.7: Response time for QoS=80% versus number of channels (simulation).
Figure 5.8: PDF of the proposed model with general distributions.
latency for real-time underwater video applications even when using the maximum number of transmission channels.

5.4 Discussions

Video streaming using underwater wireless optical communications is essential for many underwater monitoring and exploration applications. Delay sensitive applications that require live video streaming mandate further investigations on how to make better designs of UWONs. Implementing stochastic models facilitate the analysis of any tradeoffs between the E2E delay, packet dropping probability and the appropriate number of channels in cases when a multi-channel configuration is explored. This analytical work introduced the queue model for such a delay-sensitive network, and investigated the analytical derivations of the proposed queue model. The results discussed the verifications of the analytical work against the associated simulation. The results show a strong match between the analytical and simulation results. Our proposed model should provide the network designers with the necessary tools to evaluate various system’s performances considering the QoS constraints we proposed.

The next chapter will provide our comprehensive conclusion on all of this thesis contributions and will end with our prospectus on the future demands and directions of the research on underwater video transmission.
Chapter 6

Concluding Remarks

6.1 Summary

In the first part of our work, we evaluated the performance of a low-power, cost-effective, and Underwater Wireless Optical Communication based real-time video system employing Quadrature Amplitude Modulation and Phase-Shift Keying modulations. We take into account various underwater channel link conditions and analyzed both overall Bit Error Rate and video quality. Performance results reveal that live video streaming is not only feasible over different ocean water types but also with good image quality. The experimental setup for real-time video streaming is using green laser sources. We implemented Quadrature-Phase-Shift-Keying, and up to 8-QAM modulations in different underwater channels. We demonstrated not only that video streaming is possible in one of the most turbid ocean water types, but also with good quality [9].

We further proposed using bi-directional communication links for the purposes of underwater ultra high definition and live video streaming on the downlink channels while providing the feedback control messages on the uplink channels [10]. The additional uplink channel provides necessary feedback about the channel conditions, the possibility of using this to transmit and receive control messages, and real-time commands for maneuvering the Remotely Operated Vehicles. Furthermore, when a wireless optical feedback link is established, movements of multiple robots can be coordinated where the vehicles can move freely and send signaling data and receive
further maneuvering instructions in real-time. The feedback received as well on the underwater channel conditions enables the instantaneous throughput adaptations to the noise levels and transmission power, and thus helps in reducing the energy loss while improving the modulation and coding schemes. We experimentally demonstrate the feasibility of the proposed systems and evaluate the performance under higher orders of QAM implemented with OFDM modulations. We examine our system by deployments in various underwater channel conditions and analyze the throughput and quality of the received UHD live video streams. The results reveal that UHD video streaming is possible not only in the traditional uni-directional communication setup but also where feedback control messages are established through bi-directional links. Table 6.1 summarizes the achieved results in our work [10] against the previous systems or experiments.

We also extended our analysis and provided an analytical study that will enable researchers to make the best design of network topologies to meet the optimum QoS for the delay and packet loss when using UWON. Also, to provide researchers with performance means to design an optimal routing policy for contingency planning and to overcome the non-line-of-sight situations. Moreover, we hope to help engineers design a multi-channel system with optimal capacity assignment to each underwater wireless optical channel. In order to make this possible, we examined the performance of video transmission over an UWON system that is employing multi-channel diversity gain from a single sender through multiple channels underwater to a single receiver. We examined this network using an $M/G/1$ stochastic model to quantify the system’s performance. We developed an approximate expression for the probability of blocking at the receiver side considering an acceptable QoS for a given a minimum end-to-end delay. Given those constraints, we developed an expression for the minimum number of channels that can provide us with that acceptable QoS value. Finally, we performed simulation measurements to validate our model.
Table 6.1:
Summary of technological developments

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6.2 Future Work

Mobility of the source and destination is of so much importance in implementing field trials of UWON. Localization and tracking mechanisms are required to eliminate or minimize the pointing errors resulting from vehicles moving freely underwater. This is key in the practical implementations of fully autonomous underwater vehicles, remotely operated vehicles, and underwater robots. Another area that can be investigated is in the experimental implementations of multi-channels UWON configurations. This is important in order to optimize the video reception, enhance the reliability of the overall system. It is possible that this technique is contributing to the extension of the coverage ranges. Also, implementing error correction mechanism to enhance the reception and possibly to extend the coverage range of the existing systems. It is encouraged to pursue future research in the directions of more of field trials, experiments, and testbeds for UWON systems and platforms.
REFERENCES


Publications